2002

Force-attenuating characteristics of ice hockey shin guards: An investigation of the knee and tibial sections of varying quality shin guards.

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Force Attenuating Characteristics of Ice Hockey Shin Guards: An Investigation of the Knee and Tibial Sections of Varying Quality Shin Guards.

by

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A Thesis
Submitted to the Faculty of Graduate Studies and Research
through Human Kinetics
in Partial Fulfillment of the Requirements for
the Degree of Master of Human Kinetics at
the University of Windsor

Windsor, Ontario, Canada

2002

0-612-75829-X

ABSTRACT

The purpose of this experiment was to test the mechanical response of varying quality ice hockey shin guards under appropriate impact conditions. Junior shin guards (n=5) and adult shin guards (n=14) were analyzed independently. The results of the junior experiment revealed that many shin guards included in the experiment sustained some degree of material damage. However, even in a damaged state, variations in mechanical response to impact conditions did exist between the shin guards. The results of the adult experiment revealed that some shin guards used in the experiment sustained some degree of material damage. Significant interaction effects ($p<0.05$) of shin guard and impact energy level were revealed for all ANOVAs performed that included two or three impact energy levels. For the ANOVAs performed including only one impact energy level, significant main effects ($p<0.05$) of shin guard were revealed. Similarly to the junior experiment, not only did adult shin guards vary from one another in their mechanical responses to the impact conditions, variations in mechanical responses also existed between the tibia and knee locations of any one shin guard. Softer or more compliant shin guards, as characterized by lower loading rate values, did tend to reduce peak force, and increase time to peak force. As a result, more compliant shin guards transmitted less of an impulse and therefore absorbed more energy in the process. These findings suggest that more compliant shin guards can offer a degree of injury prevention for athletes. Implications of the findings are discussed in light of experimental design limitations.

DEDICATION

To my parents Judith and George Fournier, for always providing me with a loving and supportive environment; for believing in my abilities; and for always giving me the little nudge I needed.

To my sisters Michelle and Kerry and my brother Gregory, for their love; and for providing me with an unrelenting drive to succeed.

And finally, to my love Sean, for your overwhelming love, warmth and support; and without whom I would be lost.

ACKNOWLEDEMENTS

I wish to sincerely thank Dr. Wayne Marino for providing me with a positive learning environment and an unforgettable experience at the University of Windsor. His patience, knowledge and support have been instrumental in my academic growth and the successful completion of this thesis.

I wish to offer my sincerest gratitude to my thesis committee members Dr. Jim Potvin and Dr. William Altenhof for their invaluable contributions. I would especially like to thank Dr Jim Potvin, for his support and expertise and for continuously challenging me at a level necessary to learn.

I would like to thank the faculty members in Human Kinetics for opening many doors to my academic future. Their broad range of expertise has provided me with a solid foundation on which to build my continuing academic career. I would especially like to thank Dr. Patricia Weir, for always having the time and suggestions when they were needed. My experience at the University of Windsor would most certainly have been lacking without the challenging demands put forth by the faculty members in Human Kinetics.

Finally, I would like to thank the hockey equipment manufacturers for providing the shin guard specimens used in the investigation, and for contributing to the academic research in the area of protective equipment testing.

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OPERATIONAL DEFINITIONS OF TERMS

Acceleration (average)-The rate of change in velocity over a finite change in time ($a_{avg} = \Delta v/\Delta t$).

Acceleration (instantaneous)- The instantaneous change in velocity at time *t*, found by taking smaller and smaller values of Δt and corresponding smaller and smaller values of Δv ($a_{inst} = \lim_{\Delta t \to 0} (\Delta v/\Delta t)$ or $a_{inst} = dv/dt$).

A/D Converter- A device that is capable of converting an analog signal to a digital signal.

Bone Bruise-A direct impact to bone resulting in inflammation, tenderness and pain.

Bursa(e)-Synovial fluid filled sacs that reduce friction between two body parts moving over one another (typically a tendon moving over a bone).

Bursitis-Inflammation of one or more bursa(e).

Contusion-A condition in which the tissue below the skin is damaged resulting in inflammation, but the skin is not broken.

Edema-An abnormal accumulation of interstitial fluid in tissue.

Energy-The capacity for doing work in any system.

Force-A vector quantity describing the action of one body on another.

Force Transducer / Load Cell / Strain Gauge-A device that converts one form of energy into another. A displacement value is converted to an electrical energy value (volts) and is in turn converted to a more applicable form of energy such as force (Newtons).

Fracture-Any break in a bone.

Gravitational Acceleration-Results from a gravitation force (or pull) exerted on any object ($9.81\ m/s^2\downarrow$).

Hematoma-Contusions that have had excessive blood and lymph flow into the damaged area and have as a result formed a mass of blood and dead tissue.

Impact-A collision characterized by the exchange of a large force during a small time interval.

Impulse (linear)-The integral of a force-time function ($I = \int F\, dt$).

Inflammation-The localized protective response to tissue injury in order to dilute or destroy the infecting agent or injured tissue.

Interstitial Fluid-The portion of extracellular fluid that fills the microscopic spaces betweens the cells of the tissue.

Kinetic Energy-A component of mechanical energy of a body resulting from its motion.

Mass-The quantity of matter in an object.

Mechanical Energy-The sum of kinetic and potential energy.

Momentum (linear)-The vector result from the product of a scalar mass and a velocity vector ($\mathbf{L}=m\mathbf{v}$).

Potential Energy-A component of mechanical energy of a body resulting from its position from some referenced position.

Velocity (average)- The rate of change in position with respect to time ($\mathbf{v}_{avg} = \Delta\mathbf{r}/\Delta t$) .

Velocity (instantaneous)- The instantaneous change in position at time t, found by taking smaller and smaller values of Δt and corresponding smaller and smaller values of $\Delta\mathbf{r}$ ($\mathbf{v}_{inst} = \lim_{\Delta t\to 0} (\Delta\mathbf{r}/\Delta t)$ or $\mathbf{v}_{inst} = d\mathbf{r}/dt$).

Chapter 1

Introduction

Ice hockey can be regarded as one of the most popular sports in North America. Ice hockey can also be regarded as one of the most violent sports played today. As a result, injuries that occur in the sport of ice hockey have generated much interest in the scientific literature. In order to reduce the prevalence of injury in ice hockey, factors that contribute to injury must be investigated. Therefore, it is important to identify where on the body injuries occur, what the mechanisms of injury are, the injury type and severity, and how the injuries can be prevented.

Many epidemiological studies have investigated the anatomical areas most frequently injured during ice hockey (Biasca, 1995: Bouchard, 1977: Daly, 1990; Ferrara & Schurr, 1999; Jorgensen & Schmidt-Olsen, 1986; Lorentzon, 1988a; Lorentzon, 1988b; Mölsä, 1997; Sim, 1987; Tegner & Lorentzon, 1991). Depending on the injury classification determined by any given investigator, the anatomical areas most often injured were generally classified as follows: head/neck, shoulder, arm/hand, thorax, hip/thigh, knee, and leg/foot. The anatomical areas with the largest amount of injuries attributed to them were usually the lower and upper extremities followed by the head/neck (Biasca, 1995; Ferrara & Schurr, 1999; Jorgensen & Schmidt-Olsen, 1986; Lorentzon, 1988a; Lorentzon, 1988b; Mölsä, 1997; Sim, 1987; Tegner & Lorentzon, 1991). Although injury can occur at numerous anatomical locations on the body, these injuries cannot be investigated fully without understanding the mechanisms that cause them.

Mechanisms that cause injury in ice hockey have been investigated extensively (Biasca, 1995; Bouchard, 1977; Daly, 1990; Ferrara & Schurr, 1999; Jorgensen & Schmidt-Olsen, 1986; Lorentzon, 1988a; Lorentzon, 1988b; Mölsä, 1997; Sim, 1987; Tegner & Lorentzon, 1991). The mechanisms most often reported during injury include: collisions with other players (teammate and opponent), collisions with equipment (boards and goalposts), and impact from implements (pucks and sticks) (Biasca, 1995; Bouchard, 1977; Daly, 1990; Lorentzon, 1988a; Lorentzon, 1988b; Mölsä, 1997; Sim, 1987; Tegner & Lorentzon, 1991). The mechanisms present during ice hockey have the potential to cause a variety of injuries that can range in type and severity.

Numerous types of injuries that occur in ice hockey have been reported in the scientific literature including: contusions, sprains, strains, dislocations, and fractures (Biasca, 1995; Bouchard, 1977; Lorentzon, 1988a; Lorentzon, 1988b; Mölsä, 1997). With such a large variety in the type of injury occurring in ice hockey, a large variety in the severity of the injury can be expected as well. In the scientific literature, severity is often classified in terms of days lost from practice or game sessions (Lorentzon, 1988a; Lorentzon, 1988b; Mölsä, 1997; Tegner & Lorentzon, 1991). Injuries of minor severity are often classified with 0 to 7 days lost, injuries of moderate severity are often classified with 8 to 28 days lost, and injuries of major severity are those injuries that result in greater than 28 days of practice or game sessions lost. With injury type and severity a major concern in ice hockey today, steps must be taken to ensure protection against the potential for injury.

Protection against injury has become an integral part of the ice hockey experience. With increasing player size and skill levels, ice hockey players today must protect themselves against potential injuries. As a result, numerous pieces of protective equipment have been developed for the sport. Each piece of equipment must effectively protect against typical injuries that occur at the anatomical area the piece of equipment was designed to protect. An example of one such piece of protective equipment would be the ice hockey shin guard.

Statement of the Problem

Ice hockey shin guards are designed to protect the knee and leg against potential impact injuries. Injuries the shin guard is designed to protect against are for the most part, not considered to be life threatening. However, injuries that do occur at the knee and leg during ice hockey can range from minor severity levels to major severity levels (Jorgensen & Schmidt-Olsen, 1986). Shin guards must therefore be effective at protecting the knee and leg against the potential for various types of injuries. The problem is, little attention in the scientific literature has been given to protective equipment that is designed to protect against non-life threatening injuries.

The aim of this experiment was to investigate the force attenuating characteristics of varying quality shin guards. The primary objective of the investigation was to measure mechanical response of various shin guards and evaluate each shin guard's ability to attenuate impact forces. Through the testing and evaluation of shin guard force attenuation characteristics, possible improvements to design may be suggested. The ultimate goal of any suggestion would be to increase the shin guard's ability to attenuate impact forces and, therefore, enhance its ability to prevent impact injury to the lower extremity in the sport of ice hockey.

Chapter 2

Review of Literature

Injuries of varying types and severity are apparent in the sport of ice hockey. Injuries are frequent and can occur at all age levels. It is therefore important that the protective equipment used in hockey is effective at protecting all athletes against potential injuries. Before the effectiveness of any piece of protective equipment can be evaluated, there must be a clear understanding of which athletes are at risk of being injured, the injuries that typically occur and the mechanisms that contribute to the injuries. In the case of shin guards, there must be a clear understanding of the athletes using the shin guards, the injuries the shin guards are designed to protect against, and the mechanisms that cause these injuries. With an increased knowledge of the epidemiology of knee and leg injuries in hockey, protective equipment such as hockey shin guards can be evaluated.

Athletes at Risk

Regardless of the injury potential present in hockey, participation in the sport continues to increase for all age levels of both male and female athletes (Sim, Simonet, Melton, & Lehn, 1988). As with many pieces of protective equipment in hockey, the use of shin guards is mandatory (Reid & Losek, 1999). Shin guards must therefore protect against potential injury encountered by athletes of all age levels. Some scientific literature has focused on injuries in hockey that occur at various age levels (Björkenheim, 1993; Brust, 1992; Pinto, 1999; Reid & Losek, 1999; Roberts, 1999; Smith, 1997; Stuart, 1995; Stuart &

Smith, 1995; Voaklander, 1996). Although the majority of the literature has focused on elite and professional players, injuries that occur at the youth level and at the adult recreational level have also been investigated.

Hockey is a sport that has gained tremendous popularity among North American youth. Brust, Leonard, Pheley and Roberts (1992) have stated that approximately 200 000 children play organized hockey in the United States. Stuart, Smith, Nieva and Rock (1995) have stated that there are more than 18,000 teams registered with U.S.A. Hockey. Injury prevention for athletes is necessary, even at a young age level. Strategies that have been implemented to prevent injuries at younger age levels have included: adherence to protective equipment requirements, strict rule enforcement, elimination of checking, and educational programs eliminating the norms of violence in hockey (Reid & Losek, 1999). Although the skating, stick and puck velocities are at lower levels for younger players, injuries of varying severity still occur (Brust, 1992; Reid & Losek, 1999; Roberts, 1999; Stuart, 1995). Studies that have investigated young hockey players (9-15 years of age) have noted that injuries of minor severity such as contusions are the most frequent type of injury that occurs (Brust, 1992; Roberts, 1999; Stuart, 1995). Although less frequent, injuries of major severity such as fractures, have also been reported (Brust, 1992; Roberts, 1999; Stuart, 1995). Therefore, in addition to the implementation of other injury prevention strategies, the use of protective equipment is paramount.

A considerable amount of attention in the scientific literature has been given to hockey players of adult age (Björkenheim, 1993; Pinto, 1999; Smith, 1997; Stuart, 1995). These studies have focused on high school level players (Smith et al., 1997), junior level players (Bouchard, 1977; Björkenheim, 1993; Pinto, 1999; Stuart, 1995; Watson, 1997), intercollegiate level players (Ferrara & Schurr, 1999, Pelletier, 1993), and elite or professional players (Biasca, 1995; Jorgensen & Schmidt-Olsen, 1986; Lorentzon, 1988a; Lorentzon, 1988b, Mölsä, 2000; Tegner & Lorentzon, 1991). The most frequent type of injuries sustained at this age level included: contusions, sprains and strains (Biasca, 1995; Ferrara & Schurr, 1999; Lorentzon, 1988a; Lorentzon, 1988b; Pelletier, 1993; Pinto, 1999; Smith, 1997; Stuart, 1995; Tegner & Lorentzon, 1991). Injuries of major severity such as fractures also appeared to be more frequent at this age level as compared to younger hockey players (Biasca, 1995; Ferrara & Schurr, 1999; Lorentzon, 1988a; Lorentzon, 1988b; Pelletier, 1993; Pinto, 1999; Smith, 1997; Stuart, 1995; Tegner & Lorentzon, 1991). When compared to other sports, the sport of hockey has been found to have the highest incidence of injuries among high school players in general (Pelletier et al., 1993). Sutherland (1976) noted that injuries per player per year increased from 0.02 in youth, 0.20 in high school and 2.48 in college to 3.0 in professional players. Due to the nature and popularity of the sport, hockey related injuries are projected to most likely increase (Pinto, Kuhn, Greenfield & Hawkins, 1999). Therefore, as player size and skill levels increase, protection provided by protective equipment is essential.

Some attention in the scientific literature has been given to the adult recreational player (30 years of age and older) (Voaklander, Saunders, Quinney & Macnab, 1996). Due to the popularity of recreational hockey, many recreational leagues have adopted modified rules to increase safety (Voaklander et al., 1996). Even with modified contact rules, injuries such as contusions, strains, sprains, lacerations, dislocation, and fractures do still occur (Voaklander et al., 1996). Although the incidence of injury is lower in adult recreational players, the trends appear to be similar to those observed at the elite or professional levels (Voaklander et al., 1996). Safety rules must therefore be complemented with the use of protective equipment in the prevention of injuries for adult recreational players.

Injuries Ice Hockey Shin Guards Protect Against

Biasca, Simmens, Bartolozzi and Trentz (1995) reviewed typical injuries that occurred in NHL, Hockey Canada and European hockey leagues. Using missed days as the criteria for injury, the authors determined that lower extremities injuries accounted for the majority of the games missed. Ferrara and Schurr (1999) investigated factors that predicted intercollegiate hockey injuries. Using missed days as the criteria for injury, the authors found that injury location predicted days lost. According to Ferrara and Schurr (1999), the leg/foot, knee and shoulder were found to predict the most days lost. With such a concern for minor, moderate and severe injuries occurring at the lower extremity, protective equipment must be used to protect against the potential for injury. The injuries that have been documented to occur at the knee and leg during play include; contusions, sprains, strains, lacerations, dislocations and fractures (Bouchard, 1977; Brust, 1992; Daly, 1990; Jorgensen & Schmidt-Olsen, 1986). The hockey shin guard however, was not designed to protect the knee and leg against all injuries that do occur. Shin guards are not intended to offer protection against ligamentous knee or ankle injuries, nor are they expected to prevent muscle strain injuries. Specific injuries shin guards have the potential to protect against include: bruises, contusions, hematomas, bursitis, bone bruises and fractures. With an understanding of these injury pathologies, the injury prevention requirements of shin guards become more apparent.

Injuries that occur at the lower extremity are predominantly soft tissue injuries (Daly, Sim & Simonet, 1990). Skin bruises are compression injuries that result from the accumulation of blood within the skin (Anderson & Hall, 1995). Contusion type injuries are common in the lower extremity due to its vulnerability to direct blows (Bresnahan & Redmond, 1979). Muscle contusions are injuries that result from tissue compression, and are characterized by the accumulation of blood and lymph within a muscle. Hematomas are contusions that have had excessive blood and lymph flow into the damaged area, and as a result, form a mass of blood and dead tissues. The severity of a contusion can range from first degree to third degree severity. A first-degree contusion can be characterized by little restriction in range of motion. A second-degree contusion can be characterized by a noticeable decrease in range of motion whereas a third degree contusion can be characterized by a severe decrease in range of motion. In the case of the third degree contusion, fascial tears may also be present, allowing the muscle to protrude (Anderson & Hall, 1995). Bursae are synovial fluid filled sacs that reduce friction between one body part moving over another (Tortora, 1995) (see Appendix A, B and C for Anatomy of Knee and Leg).

Bursitis can be characterized by the inflammation of one of more bursae, and may be caused by either acute or chronic trauma (Anderson & Hall, 1995). Soft tissue injuries such as bruises, contusions, hematomas and bursitis result in similar tissue healing processes. When considering how soft tissue injuries affect athletic performance, an understanding of soft tissue healing becomes important.

Soft tissue healing occurs in a three stage process: (1) acute response, (2) repair and regeneration, and (3) remodeling (Anderson & Hall, 1995). Soft tissue damage can lead to edema and inflammation (Reid, 1992). If the edema or inflammation is left untreated, it may take several months to reorganize and be reabsorbed (Reid, 1992). To accelerate tissue healing, modalities such as ice, ultrasound or interferential therapies are often used. To minimize the inflammation, soft tissue injuries can often be treated with rest, ice, compression and elevation. It becomes apparent that inflammation due to soft tissue injuries to the lower extremity can interfere with athletic performance. According to Aspelin, Ekberg, Thorsson, Wilhelmsson and Westlin (1992), in some cases the intense pain, tenderness and swelling due to soft tissue injury may even require surgery. Proper acute care and rehabilitation of damaged soft tissue therefore plays an essential role in athlete performance.

Osseous tissue injuries can also occur at the knee and leg during hockey. Osseous injuries in hockey consist of bone bruises and fractures. Bone bruises can be characterized by trabecular microfractures that are a result of trauma (Miller, Osborne, Gordon, Hinkin & Brinker, 1998). A direct blow to the bone results in tenderness and inflammation (Manal & Snyder-Mackler, 2000), which may be associated with additional complications. Bone bruises to the patella have been linked to inhibition of the quadriceps femoris muscle, where there is an inability to activate the muscle due of inflammation and pain. A prevalence of bone bruises in patients who have sustained anterior cruciate ligament and medial collateral ligament injuries has also been documented (Miller et al., 1998). Bone bruises therefore become an important consideration when the bones of the lower extremity sustain direct trauma in hockey. Fractures are rare injuries in the sport of hockey, however when they do occur; they are of serious concern. Tibial fractures are more prevalent than fibula fractures in most events, except the most severe traumatic accidents (Bresnahan & Redmond, 1979). Osseous tissue injuries such as bone bruises and fractures have similar healing processes. When considering how osseous tissue injuries affect athletic performance and athlete return to play, an understanding of osseous tissue healing becomes important.

Osseous tissue healing occurs in a six stage process; 1) impact, 2) induction, 3) inflammation, 4) soft callus, 5) hard callus and 6) remodeling (Reid, 1992). This process can take up to several years to be completed. Similarly to soft tissue damage, inflammation due to a bone bruise can often be treated with rest, compression, ice, and elevation. Although bone bruises may require little treatment, fractures will often require extensive treatment and rehabilitation. Fracture treatment will always result in the immobilization of the fractured bone.

Acute care and rehabilitation of damaged osseous tissue will therefore play an important role in athlete performance and athlete return to play.

Mechanisms of Injury

A force can be defined as a vector quantity describing the action of one body on another body. All forces possess magnitude and direction and therefore can be represented by a vector. Forces can result in linear motion, rotary motion or a combination of the two. Hockey is an activity that has an abundance of both direct and eccentric forces. Many of the forces present in hockey are often the result of impact situations. Impacts occur when two objects collide over a small period of time and large forces are transferred to each object (Hall, 1999). In a sporting environment, forces transferred during impact may occur as a result of high velocity-low mass collisions or low velocity-high mass collisions. In hockey, impacts from objects such as pucks or sticks may be considered high velocity-low mass collisions, whereas impacts resulting from a body mass falling or sliding into equipment (boards or goalposts) may be considered low velocity-high mass collisions. When the forces transferred during impact exceed tissue tolerance levels, injury will likely be the result.

Typical impact forces present in hockey resulting in injury can be the result of: illegal play, poor technique, poorly matched players, previous injury, low tolerance to injury, inability to protect an area without restricting motion, and poor quality protective equipment (Anderson & Hall, 1995). Mechanisms that cause injury in hockey can be generally classified as follows: impacts with other players (opponent or teammate), impacts with equipment (boards or goalposts), impacts from implements (stick or puck), falling and others (skate, fighting, distention, and overuse) (Björkenheim, 1993; Bouchard, 1977; Daly, 1990; Ferrara & Schurr, 1999; Lorentzon, 1988a; Lorentzon, 1988b; Mölsä, 1997; Pelletier, 1993; Sim, 1987; Tegner & Lorentzon, 1991). Comparing the forces produced during typical hockey impacts to known tissue tolerance levels of the leg can help quantify the injury protection required of shin guards.

Injuries resulting from impacts between players (opponent or teammate), account for a considerable amount of injuries in hockey (Björkenheim, 1993; Lorentzon, 1988a; Lorentzon, 1988b; Mölsä, 1997; Pelletier, 1993; Sim, 1987). Player impacts can be the result of intentional checking or unintentional collision with opposing players or teammates. Pfoerringer and Smasal (1987) reported typical skating speeds of 8.89-13.33m/s depending on the skill level whereas Sim, Simonet, Melton and Lehn (1987) reported skating speeds ranging from 9.54-12.12m/s and backward skating speeds ranging from 6.82-7.57m/s, depending on the skill level. In addition, Brust et al. (1992) noted that players as young as 11-13 years could reach skating velocities of 8.89m/s. Sliding speeds as high as 6.67m/s have also been reported (Pfoerringer & Smasal, 1987; Sim, 1978). It is apparent that the magnitude of the skating and sliding speeds become important when considering injuries that result from collisions with other players and equipment (boards and goalposts).

Injuries resulting from the impact of implements such as pucks and sticks, also account for injuries in hockey (Daly, 1990; Ferrara & Schurr, 1999; Tegner & Lorentzon, 1991). Puck velocities have been reported between 24.24-39.38

m/s depending on the skill level and shot type (Sim et al., 1978). A standard puck velocity of 31.1 m/s is used by The Canadian Standards Association (CSA) when testing hockey helmet facemasks. It has been reported that some boys as young as 12 years are capable of generating such a puck velocity (Norman, Bishop and Pierrynowski, 1980). In addition, Brust et al. (1992) noted that players as young as 11-13 years could reach puck velocities of 26.7 m/s. Angular stick velocities ranging from 20.2-39.3 rad/s have also been reported (Sim et al., 1987) and are also important when considering impact situations from implements. The magnitude of puck and stick speeds becomes important when considering injuries caused by impacts from implement. If the forces transferred during impacts from players or implements exceed tissue tolerance levels, injury will likely be the result.

Testing Protective Equipment

Anderson and Hall (1995) have proposed some protective equipment design factors that may reduce potential injury. These factors include; 1) increase the area of impact, 2) transfer and disperse the impact area to another area of the body, 3) limit the relative motion of a body, 4) limit deformation and displacement by adding mass to the body part, 5) reduce friction between surfaces in contact with each other, 6) absorb energy and 7) use materials that can be cleaned and are resistant to bacteria, fungus and viruses. In order for protective equipment to be effective, it must also fit the anatomy of all athletes, allow freedom of movement and attenuate excess force (Adrian & Cooper, 1995). In addition, protective equipment must be evaluated periodically to ensure that attenuation characteristics have not diminished (Adrian & Cooper, 1995). Therefore, any method for testing protective equipment must incorporate some of these general design considerations.

Methods involved in testing protective equipment must incorporate knowledge concerning the athletes who are at risk, the mechanisms that have the potential to cause injury and the types of injuries that occur. The testing apparatus and the characteristics tested must therefore be tailored to meet the specific injury prevention characteristics of a given piece of equipment. One testing apparatus that is used to test protective equipment subjected to impact forces is the drop test rig. Drop test experiments involve a series of controlled impacts intended to simulate real life conditions. A known mass is dropped in a guided fall by twin wires or a monorail frame onto an anvil. The anvil surface can be flat, cylindrical or a "kerbstone". The "kerbstone" surface consists of two surfaces that make an angle of 100-110 degrees (Bicycle Helmet Safety Institute, http:/www.helmets.org, 2001). A specimen such as a helmet can be mounted on the drop weight and dropped onto the anvil, or a specimen such as a piece of padding can be impacted while placed on the anvil. Data can be collected through accelerometers mounted within the drop mass or from force transducers mounted under the specimen being impacted at the anvil. The data collected with these instruments can be used to determine mechanical response of the material being tested. The performance of the material tested under realistic conditions can then be evaluated against known human tissue tolerance values resulting in injury. These comparisons can then help determine the effectiveness of protective equipment in preventing injury.

Various types of protective equipment and their force attenuating characteristics have been investigated for their ability to provide protection against injury due to impact forces. Unfortunately, investigations of force attenuating characteristics of ice hockey shin guards have yet to be published in the scientific literature. Impact tests that have been performed on other types of materials may however provide insight into the development of test procedures for shin guards. Although the specific purpose of each piece of equipment may differ, the requirement of impact force attenuation remains the same. The ability of a piece of protective equipment to attenuate impact forces must be measured through several mechanical characteristics. Establishing a testing procedure to evaluate the force attenuating capabilities of shin guards should therefore include some of the mechanical characteristic measurements used in impact testing in general.

Various types of material have been subjected to impact testing in the field of kinesiology. Materials used in protective padding, footwear, rehabilitative braces, and sport equipment have been investigated for their potential to attenuate impact forces and as a result, their ability to prevent against injury. Several common mechanical characteristics have been measured in these investigations and therefore should be included when establishing a testing procedure for shin guards.

Impact Testing of Soccer Shin Guards

Impact testing of soccer shin guards has received some attention in the scientific literature. Although the mechanisms of injury in soccer may be different from those in hockey, the purpose of lower extremity protection remains similar for both shin guards. Similarly to hockey players, soccer players are at high risk for soft tissue injuries to the lower extremity (Boden, 1999). Soccer shin guards are considered to be most effective at reducing abrasions and contusions to the lower extremities (Boden, 1999). Unfortunately, fractures do occur in the sport of soccer, and very often occur when the soccer shin guard is in use (Bir, 1995; Boden, 1999; Francisco, 2000). It is therefore no surprise that much of the research investigating the effectiveness of soccer shin guards has focused on the ability of the shin guard to reduce fractures (Bir, 1995; Boden, 1999; Francisco, 2000). The mechanism of injury most commonly responsible for causing fractures in soccer is the slide tackle (Boden, 1999; Francisco, 2000). Slide tackles usually occur at relatively low velocities (1-5 m/s), whereas kicking collisions can reach higher velocities (18-24 m/s) (Francisco, Nightingale, Guilak & Garrett, 2000). Therefore, as in hockey, impact situations in soccer may be occurring at low and high velocities. To determine the force attenuating capabilities of soccer shin guards, several mechanical and design characteristics have been measured. The mechanical characteristics tested under impact situations have included; force transmitted through the shin guard, principal strain of a tibial model the shin guard was mounted on and the contact time during impact (Bir, 1995; Francisco, 2000). In addition, some design characteristics have been tested under impact situations and have included; weight, thickness and length of the shin guard (Bir, 1995; Francisco, 2000). Although soccer players are not subjected to comparable high velocity-low mass objects (pucks and sticks) as are hockey players, soccer players are subject to similar low velocity-high mass forces from other players (kicking and slide tackles) that result in injury (Bouchard, 1977; Boden 1999; Bir, 1995; Francisco, 2000). Therefore, even though soccer and hockey are two completely different sports, the theory applied in evaluating the force attenuating capabilities of soccer shin guards may be applied to hockey shin guards.

Bir, Cassatta, and Janda (1995) investigated force attenuating capabilities of soccer shin guards. Using a pendulum impact rig, the authors determined the total force transmitted to the model tibia during impact. An impact was delivered to a model tibia mounted with a soccer shin guard, with load cells located at the knee and ankle ends. The forces measured at the knee and ankle were added to obtain the total force transmitted to the model tibia. An impact force of ~2300N, representative of a forceful kick, was applied to each shin guard. A series of impacts were delivered to the model tibia under varying environmental conditions (0°C, 20°C, and 38°C). The authors found that all soccer shin guards tested, significantly reduced the amount of force transmitted to the model tibia (40-77.1%). According to the authors, the shin guard's ability to reduce the amount of force transmitted to the model tibia was significantly reduced under the hot (38°C) condition. Bir et al. (1995) concluded that under various environmental conditions, soccer shin guards could prevent injuries that might typically occur without a shin guard.

Francisco et al. (2000) also evaluated soccer shin guard capabilities in preventing tibia fractures. Using a monorail drop rig, an impact was delivered to a model tibia mounted with a soccer shin guard. The authors measured the maximum end load, the maximum principal strain and the contact time that resulted from the impact. In addition to mechanical characteristics, Francisco et al. (2000) investigated design characteristics of soccer shin guards. Therefore, the influence of weight, thickness and length of shin guards were evaluated during impact testing. Impact velocities between 1-5 m/s were used to simulate slide tackles. Mechanical and design characteristics of soccer shin guards were tested at various drop heights. Two load cells placed at the knee and the ankle ends of the model tibia measured the maximum end load transferred to the model tibia during impact. Forces recorded at the knee and ankle summed to be the total force transferred by the impact. The model tibia was also mounted with a strain gauge on the posterior side to measure maximum principal strain applied during impact. In order to ensure the reliability of the synthetic model, cadaver tibias were subjected to the experimental impact conditions for comparative purposes. Although the model tibia displayed slightly lower peak force values, larger principal strain values, and longer contact times, the mechanical responses of the synthetic model were similar to the average cadaver specimen. In addition, impacting the cadaver tibias to the point of failure required an average peak force of 2927 $\pm$ 403 N.

Using the impact conditions of 0.2, 0.3, 0.4, and 0.5m corresponding to 6.1, 10.2, 13.1, and 15.3J, Francisco et al. (2000) found that the average shin guard only attenuated between 11-17% of the maximum end load, and was only significant at the higher drop heights. The maximal principal strain showed a 45-51% reduction with the average soccer shin guard, and was significant at all drop heights. Although there was an 18-29% reduction in contact time with the average shin guard, it was not found to be significant at any drop height. The differences measured among the material types showed that certain materials attenuated significantly more force than others. No significant differences were noted between the material types for maximum principal strain. The contact time however, was significantly more reduced in certain materials as compared to others. When evaluating the design characteristics, the authors found that the weight of the soccer shin guard correlated well with the three measured mechanical characteristics. The thickness of the shin guard did not correlate as well, however the correlations increased at higher drop heights. The length of the soccer shin guard only correlated with the measure of principal strain. Francisco et al. (2000) suggested the following improvements to soccer shin guard design: 1) the impact force should be distributed along the length of the shin guard, 2) that contact times should be increased through increased compliance of the shin guard and 3) the shin guard should achieve an optimal balance between protection and freedom of movement to ensure athlete satisfaction.

Impact Testing of Athletic Footwear

A considerable amount of attention has been given to the testing of force attenuating capabilities of athletic footwear. Much of the research has focused on the investigation of footwear material and its influence on ground reaction forces (McCaw, 1999; Nigg, 1987; Nigg, 1988). To evaluate the mechanical response of footwear material, several mechanical characteristics have been measured. Common mechanical characteristics tested under footwear impact situations have included; peak force, time to peak force and loading rate of force. The theory used in evaluating the mechanical response of footwear material to impact conditions may be applied to impact testing of shin guards because in essence, both types of material are intended to attenuate impact forces with the ultimate purpose of preventing injury.

Nigg, Bahlsen, Luethi and Stokes (1987) investigated the influence of running velocity and midsole hardness on external impact forces during running. The purpose of the experiment was to evaluate the mechanical response of athletic footwear under varying velocity and midsole hardness conditions. Nigg et al. (1987) obtained measurements for peak force (vertical), time to peak force, the maximal loading rate of force, the time of maximal loading rate and the maximal active force peak (horizontal). Results from varying midsole conditions revealed a slight non-significant decrease in peak force (vertical) with increased midsole hardness whereas the time to peak force remained constant for less hard midsoles and significantly decreased for harder midsoles. The maximal loading rate remained constant across the midsole conditions where the time of maximal loading rate remained constant for the less hard midsoles and significantly decreased for the harder midsoles. The authors concluded that although counterintuitive, variations in midsole hardness did not significantly affect peak impact forces (vertical) and therefore could not be attributed to better cushioning.

Nigg, Herzog and Reid (1988) investigated the effect of shoe insoles on vertical impact forces during running. One purpose of the experiment was to compare impact forces in running using conventional insoles and varying viscoelastic insoles. In addition to other variables, the authors measured mechanical characteristics that included; peak force, time to peak force and loading rate of force. The results of the experiment revealed peak force and time to peak force values did not change significantly with varying insoles. Although the results did reveal that the loading rate of force did significantly change depending on the insole, there did not appear to be a systematic pattern in the differences. Nigg et al. (1988) therefore concluded that various viscoelastic insoles did not significantly alter ground reaction forces during running.

McCaw, Heil and Hamill (2000) investigated the effect of investigator comments about shoe construction on the impact forces measured during walking. Although the main purpose of the experiment was to determine if subjects altered their walking strategies based on shoe construction comments made by the investigators, some of their findings may provide insight into evaluating force attenuating characteristics of footwear material. According to McCaw et al. (2000), energy absorption has been identified as an important factor in the prevention and development of gait related injuries. Therefore, one purpose of midsole material is to attenuate impact forces. In addition to several other variables, the authors measured four mechanical characteristics associated with each midsole material. These mechanical characteristics included peak vertical force, time to peak vertical force, impulse to peak force, and loading rate of force. McCaw et al. (2000) did not find any statistically significant differences in peak force, time to peak force or impulse to peak force. The loading rate did however show a statistically significant shoe main effect. The statistical procedures revealed that loading rates of harder shoes were significantly higher than loading rates of softer shoes. According to McCaw et al. (2000), the results of the experiment supported the theory that the ground reaction forces during initial ground contact in gait experiments are most appropriately described by the loading rate.

The mechanical characteristics most often investigated in athletic footwear impact testing have been peak force, time to peak force and loading rate of the force. Therefore, it would be appropriate to investigate these mechanical characteristics when testing the force attenuating capabilities of shin guards. Unfortunately, compounding factors may have resulted in contradictory results when evaluating mechanical characteristics of footwear material under impact conditions. Internal mechanisms such altered muscular activity due to the perception of impact, have been shown to contribute to force attenuation during human locomotion (Cole, Nigg, van den Bogert & Gerritsen, 1996). Therefore, it is important to note that the lack of significant changes in mechanical characteristics of footwear material may not accurately represents the material's ability to attenuate impact forces.

Impact Testing of Other Sport Equipment

Impact testing of other sport equipment has also received some attention in the scientific literature. Although the purpose of each piece of equipment may be different, most pieces of protective equipment are subjected to impacts conditions. Whether the equipment is worn on the body or is part of the sport environment, its general purpose is to attenuate impact forces and provide injury protection to the athlete. In addition to the methods used and variables measured in this area of research, the interpretation of the results may be applicable to results obtained from shin guards testing.

Potvin & Marino (1998) investigated the impact characteristics of two types of hockey arena boards. A pendulum impact system was used to determine the force attenuating characteristics of RAITA (brand name) and standard hockey arena boards. The purpose of the experiment was to compare the energy absorption characteristics of the two types of hockey arena boards. Potvin & Marino (1998) collected data for three performance measures: the work and energy during impact (for validation purposes), the stiffness of the boards and the amount of energy absorbed by the boards during impact. The authors first compared the kinetic energy delivered by the pendulum to the work value measured during contact for each board. The ratio of energy delivered to the measured work done was determined to be very close to a 1:1 relationship in both cases. The authors could therefore conclude that the test used was valid and reliable for the range of energy values used in the experiment. Lower peak force values were observed with the RAITA boards in comparison to the standard hockey arena boards. The authors noted that the difference increased as the impact energy delivered increased. Potvin & Marino (1998) plotted the impact energy levels against the peak force values recorded and percent differences between the two types of hockey arena boards were given in terms of peak force per joule of initial energy. The line of best fit for the RAITA boards data had a less steep slope than the line of best fit for the standard boards. These results indicated that the peak forces recorded by the RAITA boards were lower than those recorded by the standard boards across the whole energy range. The stiffness results provided evidence that the RAITA boards were more compliant and distributed the impact energy over a longer distance. The energy absorption results revealed that RAITA boards absorbed more energy than standard hockey arena boards under certain impact height conditions. Potvin & Marino (1998) therefore concluded that the RAITA boards absorbed more energy at certain impact heights, were more compliant and attenuated more of the peak force than did standard hockey boards.

Bahamonde & Malone (1997) investigated the force attenuating characteristics of playing casts. The purpose of the experiment was to test the mechanical properties of playing cast materials and their ability to absorb forces produced during impact. Impact velocity, impact area, percentage of average force absorbed compared to a no-material condition, compressive stress, modulus of elasticity and a hardness index were calculated for each playing cast using data collected from a force platform. In addition, a performance coefficient was developed to produce a ranking for all tests and each material. The performance coefficient was computed as the average effect size difference (ESD) for all five of the measured variables. Peak vertical force, percent force absorbed and compressive stress revealed significant main effects of both material and impact velocity and significant material by impact velocity interactions. The impact areas did not show significant changes with the increase of impact velocity. The modulus of elasticity and performance coefficients did show some significant differences between certain materials. Bahamonde and Malone (1997) could therefore conclude some materials used in playing casts were more effective at attenuating impact forces than others.

Greenwald, Janes, Swanson, and McDonald (1998) investigated dynamic impact responses of cadaveric forearms using a wrist brace. The purpose of the experiment was to evaluate dynamic impact responses of braced and unbraced wrists using snowboarding wrist guards. Force-time plots revealed four distinct loading phases prior to failure. Impulse and vertical velocities were calculated for each loading phase. The results of the experiment revealed that the peak forces measured by a force platform for forearms with wrist braces at each loading phase, were significantly higher than those measured for unbraced forearms. The authors noted that these results suggested that the stiff braces were resisting wrist dorsiflexion and therefore potential injury. Times to each loading phase did not reveal significant differences between the braced and unbraced groups. The impulse values calculated at each loading phase did reveal that braced forearms had significantly higher values than did the unbraced forearms. The authors noted that these results suggested the increased impulse to the constant mass caused a greater reduction in momentum of the braced wrist and subsequently decreased its velocity. In addition, Greenwald et al. (1998) noted that the wrist braces had the most dramatic effect during the two initial loading phases. Greenwald et al. (1998) were able to conclude that wrist braces did alter the dynamic loading characteristics of cadaveric wrists. Although the wrist guards may have provided a prophylactic effect at low impact energies, they had little effect at the higher impact energies.

Impact testing of various sport equipment, has produced findings that may be useful when testing shin guards. Regardless of which piece of equipment is being considered, the ultimate purpose of each piece of equipment is to attenuate impact forces and protect the athlete against potential injury. In addition to the testing methods used and variables measured in this area of research, the analysis methods used and interpretation of the results may be applicable to results obtained from shin guards testing.

Impact Testing of Hip Padding Material

Impact testing of elderly hip padding systems has produced literature that may have some applications in testing force attenuating capabilities of protective sports equipment. Methods used and mechanical characteristics measured in hip pad testing have been very similar to those used in sport equipment testing (Okuizumi, 1998; Parkkari, 1994; Parkkari, 1995 Ribonovitch, Hayes & McMahon, 1995; Ribonovitch, McMahon & Hayes, 1995) and therefore may provide additional support in the determination of impact testing procedures for shin guards.

Robinovitch, Hayes and McMahon (1995) investigated a hip padding system designed to reduce the occurrence of hip fractures in the elderly due to falls. The purpose of the experiment was to evaluate the force attenuating characteristics of energy shunting and energy absorbing hip padding systems. The mechanical responses of the padding systems were tested using a pendulum impact rig. Each padding system had identical surface areas and geometry. Mechanical characteristics investigated included externally applied force (load cell on pendulum head) and femoral reaction force (load cell on femur). Baseline force levels were established by impacting the femur with only minimal soft tissue covering the impact site. The baseline values were then used to determine percent reduction in recorded peak forces. The authors determined that the greatest amount of reduction in peak force (65%) was provided by the energy-shunting hip pad system. This reduction was nearly twice the amount of reduction in peak force provided by the next best pad. The ratios between peak femoral force and peak total applied force were 0.55 for energy-shunting pads, and between 0.78 and 0.94 for all other pads. Although the hip padding systems did reduce femoral peak force values, not all padding systems reduced the force values below the mean force required to produce a hip fracture in elderly femurs. Robinovitch et al. (1995) therefore concluded that the padding systems tested could prevent fractures under certain fall impact situations. These situations included falls that resulted in an impact being absorbed by an area greater than simply the hip region and falls involving femurs with strengths that are greater than the in-vitro elderly mean fracture force of 4100 $\pm$ 1600 N (deformation rate of 100mm/s).

Robinovitch, McMahon and Hayes (1995) also conducted a study investigating force attenuating abilities of trochanteric soft tissues during impacts from falls. The authors investigated the effect of soft tissue cushioning in obese individuals with respect to potential hip fractures. Robinovitch et al. (1995) tested trochanteric regions of nine cadavers using a pendulum impact rig. A surrogate pelvis was covered with trochanteric soft tissue and then impacted at various force levels. In order to determine the amount of energy absorbed by the soft tissue, the deflection values of the surrogate pelvis were determined and then subtracted from the deflection values obtained with the addition of soft tissue. The area under the force-deflection curve for each padding system was then calculated to be the amount of energy absorbed by the soft tissue. Robinovitch et al. (1995) determined that significant effects for both peak femoral force and soft tissue energy absorption existed. The authors noted that as tissue thickness increased, peak force decreased and soft tissue energy absorption increased. In addition to a decrease in peak femoral force, the authors also noted that as soft tissue thickness increased, the time to peak force also increased. These effects resulted in a decrease rate of loading. Impulse values were dependent on the amount of energy absorbed by the soft tissue, and therefore the area under the force-time curves was not necessarily constant. The time-deflection curves revealed that as the thickness of the soft tissue increased, the peak deflection measured also increased. The area between the loading and unloading portions of the time-deflection curves reflected the amount of energy dissipated during impact. The authors therefore determined that as soft tissue thickness increased, the peak force decreased, the time to peak force increased and peak deflection increased. Robinovitch et al. (1995) therefore concluded that increased soft tissue over the hip area could reduce the risk of hip fractures associated with falls.

Parkkari, Kannus, Poutala, and Vuori (1994) investigated the force attenuation characteristics of various trochanteric padding systems for the elderly. A pendulum impact rig was used to deliver impacts to a surrogate pelvis and femur covered with pieces of rubber of varying thickness. The first step of the experiment consisted of impacts using a constant impact velocity (3.0 m/s). In the second portion of the experiment, the impact velocity was then reduced until the peak femoral force recorded was below the known value of 2040N required to fracture the elderly proximal femur in vitro (deformation rate of 0.7 mm/s). The third step consisted of increasing the impact velocity back to 3.0m/s and then increasing the material thickness until the impact force decreased to below the 2040N in vitro threshold value. In the first portion of the experiment, the authors determined that the constant impact velocity of 3.0 m/s resulted in low force attenuation properties among all the materials tested. In the second portion of the experiment, the impact velocity was gradually reduced until the impact force was decreased below the fracture threshold. This occurred when the impact velocity was lowered to 1.6 m/s. For the third portion of the experiment, the thickness of the rubber required to reduce the impact force below the threshold value was no less than 100 mm, however the weakest material required a thickness of 140 mm. The authors noted that different materials behaved differently under the low velocity and high velocity conditions. Parkkari et al. (1994) therefore concluded that certain materials might prevent fractures under certain falling conditions in the elderly.

Parkkari, Kannus, Heikkilä, Poutala, Sievänen and Vuori (1995) specifically investigated an energy-shunting padding system used to protect the elderly hip during falls. Using a pendulum impact rig, an impact mass delivered impacts to a surrogate pelvis, femur and soft tissue. Impacts were delivered in the low energy range (78J) corresponding to a measured peak force of 6940N. Impacts were also delivered in the high energy range (132J) corresponding to a measured peak force of 10400N. In addition to the two previously mentioned impact energy levels, Parkkari et al. (1995) impacted the hip padding systems to failure using an extremely high impact energy (273J) corresponding to a measured peak force of 10400N. In this condition, each padding system was tested on a concrete floor instead of the surrogate pelvis, femur and soft tissue. The authors found that in the low energy impact condition (6940N), the padding system (including the soft tissue) reduced the peak femoral force to 1040N. During the high energy impact condition (10400N), the padding system (including the soft tissue) reduced the peak femoral force to 1810N. From the results of the experiment, Parkkari et al. (1995) concluded that the padding system used in the experiment attenuated impact forces by mainly shunting the impact energy to surrounding tissue as well as absorbing a portion of the impact energy.

Okuizumi, Harada, Iwata & Konishi, (1998) investigated a new hip fracture preventative system using a drop rig system. The purpose of the experiment was to determine the force attenuating capabilities of the padding system and to determine if the force attenuating characteristics had the potential to reduce fractures of the hip due to falls. A drop mass impacted a surrogate hip and embalmed femora covered with different hip padding systems. The impact load, impact time and maximum strain were measured using a load cell on the impact mass and a rosette strain gauge on the inferior side of the femoral neck. Impacts were conducted at increasing drop heights until fracture occurred. The peak impact force measured prior to fracture was considered to be the fracture strength. Impacts were conducted on surrogate hips (control), hips covered by a silicone gel pad, and hips covered with a silicone gel pad and resin cover. Okuizumi et al. (1998) found that as drop height increased, the silicone gel pad and resin cover showed the greatest decrease in impact load compared to the silicone gel pad alone. The authors also found that both the silicone gel pad alone and the silicone gel pad and resin cover increased the mean impact time. When the drop height was plotted against impact load, the lines of best fit for the two padding systems were situated below the line of best fit for the control. When comparing the two padding systems, the line of best fit for the results of the silicone gel pad and resin cover system had a less steep slope than did the line of best fit for the results of the silicone pad alone. Okuizumi et al. (1998)

therefore concluded that covering the hip with padding systems similar to those used in the experiment would provide effective impact attenuation and fracture prevention.

Impact testing of elderly hip padding systems has produced literature that may have some applications in testing force attenuating capabilities of protective equipment. This area of research has provided additional considerations when evaluating the force attenuating capabilities of various types of material. It would therefore be beneficial to incorporate some of the theories used in hip padding impact testing, when developing testing procedures for shin guards.

Applications for Ice Hockey Shin Guard Testing

When applying some of the impact testing procedures previously used in the literature to evaluate hockey shin guards, some important factors must be kept in mind. Like any piece of protective equipment, shin guards have certain requirements with respect to the injuries they are designed to protect against. Shin guards must protect the knee and leg against high velocity-low mass (pucks and sticks) and low velocity-high mass (players, boards and goalposts) impact situations. With an understanding of the impact conditions a particular piece of protective equipment is subject to, an appropriate testing procedure can be determined. It is therefore important that hockey shin guard testing procedures include appropriate measured variables. It is apparent that a material's response to collision or impact has commonly been evaluated through measures such as peak force, time to peak force, loading rate of force, impulse and energy absorption. Although this is not an exhaustive list of measures describing the mechanical response of a material, they can be used to evaluate shin guards in this experiment. The results obtained from these measured variables can then be used to evaluate the force attenuating properties of shin guards.

The amount of force transmitted through a shin guard can be used to evaluate a shin guard's ability to protect an athlete against injury. The equation of motion, equation (1) describes the summation of force vectors "$\Sigma\mathbf{F}$ " acting on an object as a relationship between the object's scalar mass "*m*" and its acceleration vector "**a**".

$$\Sigma\mathbf{F} = m\mathbf{a} \tag{1}$$

Ideally, a shin guard should be able to reduce the amount force applied to the soft and osseous tissues of the knee and leg. One way to quantify the reduction in force transmitted through the material is to measure the peak force. Pain and injuries to the lower leg tissues have been reported to be associated with the magnitude of vertical forces experienced during running (Cavanagh & Lafortune, 1980; Nigg, 1987; Nigg, 1988; Milani, 1997). In fact, Nigg, Denoth, and Neukomm (1981) stated that ineffective attenuation of peak impact forces that occur during running could result in microtrauma to soft tissue or bone. In order to provide injury prevention, shin guards must therefore reduce the magnitude of peak forces experienced in ice hockey. In athletic footwear research, there is an assumption that there is a relationship between impact forces and shoe cushioning (Nigg et al., 1987). According to Cavanagh & Lafortune (1980) and Rodano (1983), impact forces during running could be influenced by the material properties of the midsole material of the shoe. Lees and McCullagh (1984) found that peak impact forces were reduced for softer, thicker shoes in comparison to harder shoes. If properties of athletic footwear can be associated with the prevention of injuries (Milani et al., 1997), it may be possible that material properties of shin guards will influence the impact forces occurring in hockey. Softer or more compliant shin guards should therefore reduce the magnitude of peak forces and provide some degree of injury prevention to the athlete.

The loading rate of force is another measure that can be used to evaluate the shin guard's ability to prevent against injury. In addition to reducing the magnitude of peak forces applied to the lower leg and knee tissues, shin guard material must have the ability to reduce the rate of loading of the impact forces. It has been reported that degenerative changes in the lower extremities during running depend not only on the magnitude of force applied but also the rate at which the force is applied (Nigg et al., 1988). According to Evans and Lissner (1959), the loading rate can influence the biomechanical properties of tissues, which in turn can affect the fracture patterns of bones and the extent of soft tissue damage. A similar finding was found in an investigation of the effect of loading rate on the mechanical characteristics of spinal motion segments under compressive loading (Yingling, Callaghan & McGill, 1997). Yingling et al. (1997) concluded that load rate had an effect on the mechanical properties of vertebral motion segments, although these effects appeared to be most pronounced between quasi-static loading and higher dynamic load rates (100-1000N/s and 10000-16000N/s). According to Nigg et al. (1987), periodic stretching of soft tissue with high loading rates due to impact forces is associated with pain and injuries to the lower extremity. Impact testing of athletic footwear material has shown that loading rates of impact forces increase with midsole material hardness (deWit, 1995; Hennig, 1996; Milani, 1997; Nigg, 1987). Higher loading rates are therefore more indicative of harder materials whereas lower loading rates are more indicative of softer materials. Shin guard material properties may be expected to behave in a similar manner to athletic footwear material. If loading rate can be an indirect measure of hardness (McCaw, 2000), harder shin guards may be expected to have larger rates of loading and as a result, provide less injury prevention. Therefore in order for shin guards to protect the athlete against injury, the material must have the ability to reduce the loading rate of impact forces experienced during hockey.

The time required to attain peak force is often measured in conjunction with peak force and loading rate values. The time over which a force is applied is dependent upon the characteristics of the material the force is applied to. Animal research has shown that the application time of force is associated with the severity of injuries (Trollope, Stalmacker, McElhaney, & Frey, 1973). According to Penberthy (1952), tissue can deform without injury if the force is applied over a longer period of time. A spinal segment model developed by Lee, Kim, Lee, Hong, Jung and Goel (2000) revealed that impacts of shorter duration produced increased pressure and dynamic stiffness in the vertebral bodies. Although the stability of the spinal segment increased, the authors noted that these increased stresses would most likely produce more fractures. Athletic footwear material testing has shown that softer shoe material can delay the time to peak impact forces and as a result, reduce the loading rate (Lees & McCullagh, 1984). Ribonovitch, McMahon and Hayes (1995) found increased soft tissue thickness over the hip during a fall caused an increase in time to peak force in addition to a decreased magnitude of peak force and as a result, a decreased loading rate. According to Adrian and Cooper (1995), an ice hockey shin guard with the ability to spread force over a greater amount of time and distance might be more desirable when trying to reduce injury. Although both the distance and the time can be manipulated when designing protective equipment, increased distance or thickness of the protective equipment may result in movement restriction, potential discomfort and poor performance. Therefore, shin guard material with the ability to prolong the time of force application and as a result decrease the peak force and loading rate, may help prevent injuries to the tissues of the knee and leg during hockey.

Linear impulse is another measure often investigated in material testing. Linear impulse (**I**) is defined as the integral of a force-time function (see equation (2)).

$$\mathbf{I} = \int_{t1}^{t2} \mathbf{F}\, dt. \tag{2}$$

It is a vector quantity, which measures the effect of a force during the time the force acts (Hibbeler, *Dynamics*, 1992). If the force vector **F** acts in a constant direction, the area under the force-time curve represents the magnitude of the impulse (Hibbeler, *Dynamics*, 1992). The linear momentum vector (**L**) can be represented by equation (3), where "*m*" is the scalar mass value and "**v**" is the velocity vector value (Hibbeler, *Dynamics*, 1992).

$$\mathbf{L} = m\mathbf{v} \tag{3}$$

The equation of motion (1) can now be rewritten as equation (4) (Hibbeler, *Dynamics*, 1992).

$$\Sigma \mathbf{F} = m\mathbf{a} = m\, d\mathbf{v}/dt \tag{4}$$

Rearranging the terms in equation (4) and integrating between the limits $\mathbf{v}=\mathbf{v}_1$ at $t=t_1$ and $\mathbf{v}=\mathbf{v}_2$ at $t=t_2$, results in equation (5), also known as the principle of linear impulse and momentum (Hibbeler, *Dynamics*, 1992).

$$\Sigma \int_{t1}^{t2} \mathbf{F}\, dt = m \int_{v1}^{v2} d\mathbf{v} \tag{5}$$

or

$$m\mathbf{v}_1 + \Sigma \int_{t1}^{t2} \mathbf{F}\, dt = m\mathbf{v}_2$$

The principle of linear impulse and momentum equation (5) states that "the initial momentum of a particle at t_1 plus the vector sum of all the impulses applied to the particle during the time interval t_1 to t_2 is equivalent to the final momentum of the particle at t_2" (Hibbeler, 1992, *Dynamics*, p.179). During impact, if $m\mathbf{v}_1$ is the linear momentum of a mass m just prior to contact and $\Sigma \int \mathbf{F}\, dt$ is the sum of the impulses applied to the mass m during contact, then $m\mathbf{v}_2$ will be the linear momentum of the mass m just after impact. Knowing the mass, the initial velocity and total impulse, the rebound velocity after contact can be determined by solving equation (5) for $\mathbf{v}_2$. The rebound velocity can then be used to calculate the amount of kinetic energy the mass m possesses just after impact using equation (6), where "v" is the magnitude of the velocity vector $\mathbf{v}_2$.

$$KE = \tfrac{1}{2} m v^2 \tag{6}$$

If the kinetic energy possessed by the mass *m* prior to impact is known, and the kinetic energy possessed by the mass *m* just after impact is calculated using equation (6), loss in kinetic energy can be determined using equation (7).

$$\Delta KE = KE_{(\text{just before impact})} - KE_{(\text{just after impact})} \tag{7}$$

It therefore becomes apparent that the investigation of linear impulse during impact testing of any material can provide an indirect measurement of energy absorption.

According to Evans & Lissner (1959), tissue injury is a function of energy absorption and the rate of that absorption. Impact testing in the area of athletic footwear material has shown that energy absorption has been identified as an important factor in preventing various injuries to the lower extremities and back during locomotion (McCaw et al., 2000). According to McCaw et al. (2000), more compliant running shoes reduce impulsive loading which is associated with the onset and progression of joint degeneration. In an investigation of various synthetic midsole materials by McCullagh & Graham (1985), the findings revealed that midsole material displayed an ability to dissipate or absorb energy. In addition, the authors noted that for a particular load and load application rate, different materials absorbed different amounts of energy. McCullagh & Graham (1985) suggested that the amount of energy absorbed in each midsole decreased as the loading rate increased for the same maximal load. McCullagh & Graham (1985) therefore concluded, that the synthetic sports material tested exhibited different capacities to dissipate energy under the same impulse conditions. In a similar investigation, Clark & Frederick (1982) found materials that attenuated peak forces to a similar degree displayed different amounts of energy absorption. According to Clark & Frederick (1982), a material's ability to attenuate peak forces should not be the only criterion used in its evaluation and the ratio of energy absorbed to the energy returned by the material may provide some insight into the amount of injury protection afforded by the material.

With an understanding of previous material impact testing, and the typical impact conditions a particular piece of protective equipment is subject to, an appropriate testing procedure can be determined. It is therefore important that ice hockey shin guard testing procedures include appropriate measured variables such as peak force (Fp), time to peak force, (Tp), loading rate (LR), impulse (I) and energy absorbed (EA). The results obtained from these measured variables can then be used to evaluate the mechanical response of various shin guard material.

Chapter 3

Methods

Purpose of the Experiment

The purpose of this experiment was to test the mechanical response of ice hockey shin guards under appropriate impact conditions. With an understanding of the typical forces encountered by the knee and leg during ice hockey, a testing procedure was developed to assess the effectiveness of shin guards at attenuating impact forces. The testing procedure incorporated some of the previous methods used in impact testing, however, the impact testing attempted to simulate typical impact situations encountered by shin guards in the sport of ice hockey. A series of impacts were delivered to shin guard specimens with the aid of a twin wire drop test rig (see Figure 1 & 2). The mechanical responses of shin guards were then evaluated on the materials' relative ability to attenuate impact forces. The ultimate purpose of the experiment was to test the effectiveness of varying quality shin guards, in providing injury prevention through impact force attenuation.

Subjects

The subjects for the experiment consisted of three samples of shin guards donated by various manufacturers. A letter was sent to several shin guard manufacturers requesting specimen donations (see Appendix D). Five junior shin guards (intended for young children) and fourteen adult shin guards (intended for adults or larger adolescents) of varying quality (as specified by the

Figure 1. Twin Wire Drop Rig Apparatus Used in Experiment.

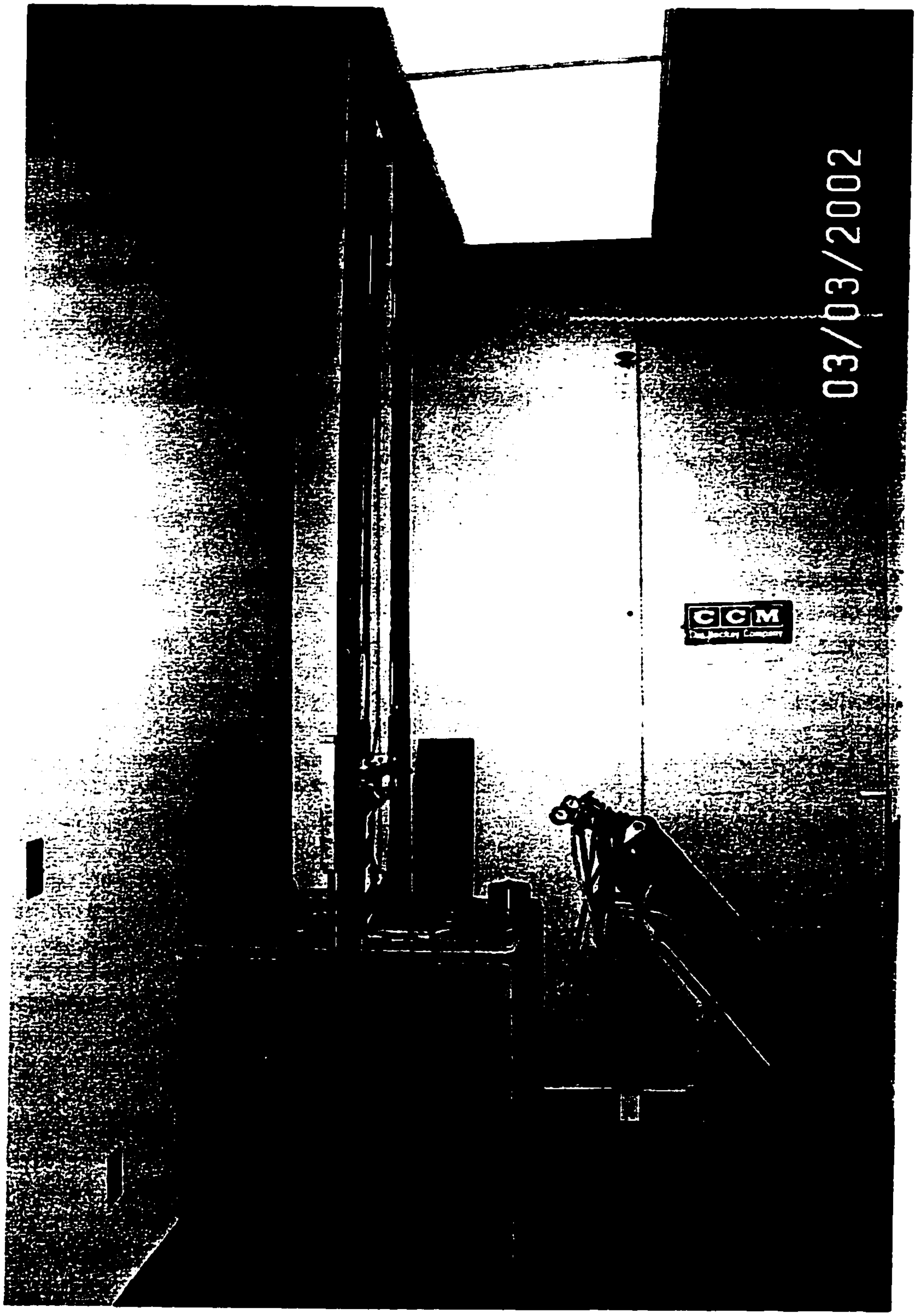
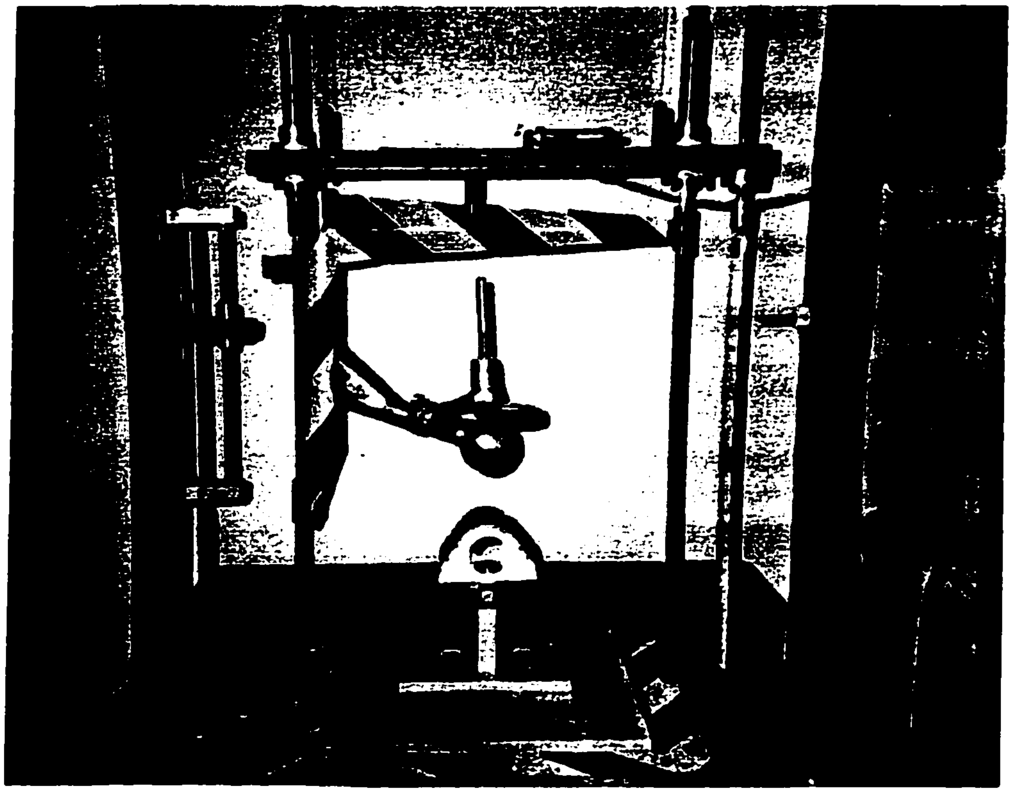


Figure 2. Leg Form and Drop Mass Used in Experiment.



manufacturer) were received from various manufacturers. The shin guards were divided into three samples including junior, mid-level adult and high-level adult.

Drop Rig Apparatus

In order to test the mechanical response of hockey shin guards, each specimen was subjected to a series of impacts of varying energy levels. The variation in quality level between junior shin guards and adult shin guards made it necessary to conduct two separate experiments. The magnitudes of the impact energy levels delivered in both experiment were representative of some impact conditions experienced in the sport of hockey. The purpose of both experiments was not to impact the shin guards to the point of failure, but rather to subject each specimen to several impacts of sub-maximal energy levels. The relative mechanical response or performance of each shin guard specimen was then evaluated. A mass of 3.3 kg was dropped from a known height to provide impact energies ranging from 3.23 to 4.88 joules for the junior shin guards and 6.47 to 19.41 joules for the adult shin guards (see Tables 1 and 2). It was assumed that the friction generated from the wires and sliding apparatus during drops was negligible. The drop mass, in both experiments, was dropped from various distances to impact a leg form mounted with an ice hockey shin guard specimen (see Figure 3).

Figure 3. Experimental Set Up (Junior and Adult Specimens).

Table 1. Estimated Impact Energies Associated with Each Drop Height (Junior Experiment).

Drop Height (m)	Final Velocity (m/s)	Kinetic Energy[a] (J)
0.100	1.40	3.23
0.125	1.57	4.07
0.150	1.72	4.88

a - Based on 3.3 kg Drop Mass

Table 2. Estimated Impact Energies Associated with Each Drop Height (Adult Experiment).

Drop Height (m)	Final Velocity (m/s)	Kinetic Energy[a] (J)
0.200	1.98	6.47
0.400	2.80	12.94
0.600	3.43	19.41

a - Based on 3.3 kg Drop Mass

Independent Variables

The three independent variables manipulated in both the junior and adult experiments included shin guard, impact energy (3 levels) and impact location on the shin guard (2 levels). As previously mentioned, shin guards were divided into three samples: junior, mid-level quality adult and high-level quality adult (as defined by the manufacturer of each shin guard). The implication of such a division was to classify each specimen according to what level of athlete might be using it. The assumption was that high-level quality adult shin guards were intended to provide more protection than mid-level quality and junior shin guards and were therefore to be used by more skilled athletes who might be exposed to higher impact energy levels. Alternatively, the mid-level quality adult shin guards might not offer the same amount of protection as high-level quality adult shin guards and therefore may not be adequate to be used at higher competitive levels.

The impact energies in both experiments were manipulated by the use of increasing increments in the drop height. The experiments included three drop heights consisting of 0.100 m, 0.125 m and 0.150 m for the junior shin guards and 0.200 m, 0.400 m, and 0.600 m for the adult shin guards. A total of 15 drops were performed at each drop height, where the first three drops were used to ensure the shin guards were firmly secured to the leg form (but not used in the statistical analysis) and an additional 12 drops were used in the statistical analysis. It was assumed that gravity was the only force acting on the drop mass before impact, and therefore the acceleration of the drop mass before impact was constant. When acceleration is constant in a system, the final velocity before impact can be expressed by the relationship in equation (8) (Hibbeler, 1992).

$$v = \sqrt{v_0^2 + 2a_c(s - s_0)} \tag{8}$$

The term "v" represents the magnitude of the final velocity vector **v**, the term "v_0" represents the magnitude of the initial velocity vector $\mathbf{v_o}$, the term "a_c" represents the magnitude of the constant acceleration vector $\mathbf{a_c}$, the term "s" represents a final position scalar in reference to an initial position scalar represented by the term "s_0". Once the magnitude of the final velocity (v) was calculated, the energy of the drop mass prior to impact was determined using equation (6). The velocity magnitude used in equation (6) was the same velocity magnitude calculated from equation (8). The calculated impact energy values associated with each drop height, for both the junior and adult experiments are represented in Tables 1 and 2. Again, the impact energy levels delivered in both experiments were not intended to approach maximal values that may be associated with material damage, but rather were intended to be representative of typical sub-maximal energy values experienced by junior and adult shin guards.

In addition to subjecting the shin guards to impact conditions of varying energy levels, the location of impact was also investigated. The three impact energy levels were delivered to each specimen at two different locations. Therefore, each specimen underwent a series of impacts for both the tibia and knee sections of the shin guard. An appropriate leg form was secured to the base of the drop rig apparatus and was then mounted with a shin guard specimen. Separate leg forms were constructed for the junior and adult shin guards.

Dependent Variables

The five mechanical response measures investigated in this experiment included peak force (F_p), time to peak force (T_p), loading rate of force (LR), impulse (I), and energy absorbed (EA). The measure of energy absorbed (EA) by the shin guard material was derived from the impulse value using the principle of linear impulse and momentum.

The first dependent variable measured in both experiments was the peak force (F_p) transmitted through the shin guard. The only force acting on the drop mass prior to impact was the force exerted on all objects by gravity. Therefore, the acceleration of the drop mass prior to impact was assumed constant at $9.81 m/s^2$. The peak force (F_p) was chosen as a dependent variable in order to gain a better understanding of the maximal force value experienced by the tissues of the knee and lower leg. Therefore, the mechanical response of peak force (F_p) provided a useful measure of evaluation for varying quality shin guards that were subjected to varying impact conditions.

The second dependent variable measured in both experiments was the time to peak force (T_p). If a particular shin guard specimen has the ability to distribute the impact force over a greater distance and longer period of time, it is assumed that the peak force (F_p) recorded by the compression force transducer at the leg form will be smaller in magnitude. In addition, if the peak forces are attenuated to a similar degree, the time over which the force is applied may become an important factor in injury prevention. The time over which a force is applied is dependent on the characteristics of the material used in the shin guards. Therefore, the mechanical response of time to peak (T_p) provided a useful measure of evaluation for varying quality shin guards that were subjected to varying impact conditions.

The third dependent variable measured in both experiments was the loading rate of the force (LR). Increased peak force values combined with shorter time to peak values will result in an increased loading rate. Higher loading rates can be considered more indicative of harder materials whereas lower loading rates are more indicative of softer materials. Shin guards that consist of more compliant or softer material may provide more force attenuation and therefore may provide superior injury prevention to the athlete. The mechanical response of loading rate (LR) therefore provided a useful measure of evaluation for varying quality shin guards that were subjected to varying impact conditions.

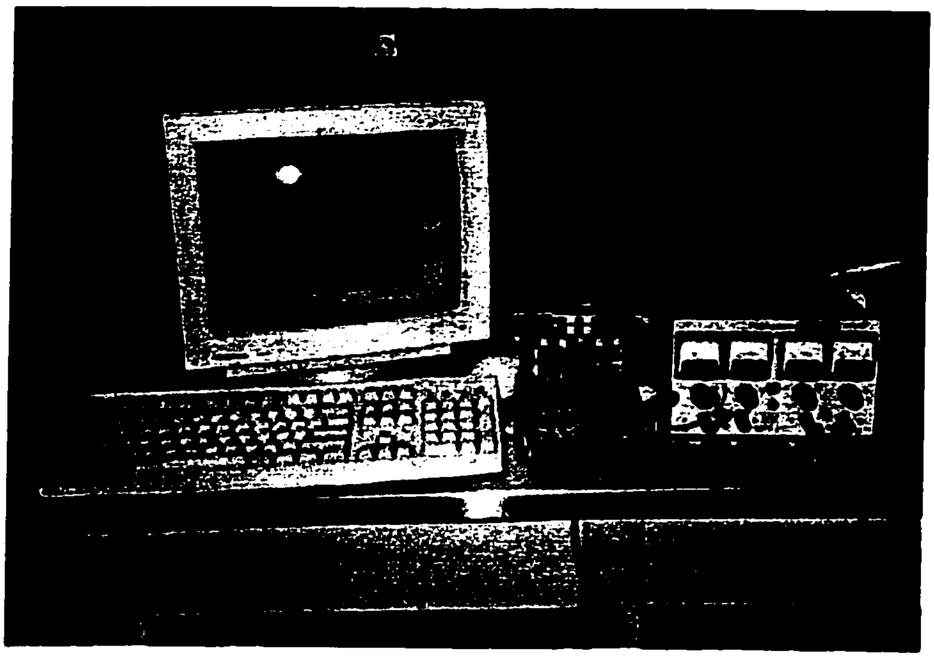
The fourth and fifth dependent variables measured in both experiments were impulse (I) and energy absorption (EA). The momentum delivered to the shin guards was constant for any given impact energy level. The amount of impulse recorded during contact without a shin guard therefore remained constant. The impulse recorded with a shin guard was dependent on the energy absorbed by the material. Shin guards with the ability to absorb energy and thereby reduce the impulse transmitted through the material may provide injury prevention to the athlete. Therefore, the measures of impulse (I) and energy absorption (EA) provided useful measures of evaluation for varying quality shin guards that were subjected to varying impact conditions.

Procedure

In both the junior and adult experiments, the shin guards were secured to an appropriately sized, metal alloy leg form (see Figure 2). The leg form used was instrumented with a National Instrument compression force transducer on the inferior side of the leg form surface. The leg form was then secured to the drop rig apparatus (see Figure 2). Once secure to the drop rig base, the force transducer was located directly under the point of impact for each drop. All impact conditions for both locations (knee, tibia) were block randomized by impact energy level for both the junior and adult experiments. A series of 15 drops were delivered to each of the shin guard specimens at each impact energy level for each location. Dependent variable values were therefore collected through the compression force transducer located directly under the impact location.

The signal collected from the compression force transducer was processed in the same manner for both the junior and adult experiments. The signal was sampled at a rate of 5000 scans per second and was collected for 600 scans (200 prior to trigger, 400 beyond trigger). The filtering cutoff frequency was determined experimentally by comparing the raw signal with a filtered signal. In order to preserve the quality of the signal, it was filtered with a low pass filter with the cutoff frequency of 500 Hz.

Figure 4. Experimental Set up (Amplifier, Power Source and Computer).



The analog signal was then amplified using a National Instrument amplifier and was converted to a digital signal using a National Instrument A/D converter. The digital signal was then processed on an IBM computer, using LabVIEW software (see Figure 4). The LabVIEW software was programmed to return values for peak force (F_p) in Newtons, time to peak force in milliseconds, the loading rate (LR) between 30-70% of the peak force value in Newtons/second, and impulse (I) in Newton-seconds. A schematic representation of the dependent variables is located in Appendix E.

Prior to the junior experiment, 10 baseline impact trials were performed for each of the drop heights used in the experiment with only a double-layered piece of foam. Dependent variable values were obtained using only the foam on the junior leg form. These values served as baseline values and were used for comparative purposes in the junior experiment. The baseline values contributed to the determination of the percent change in dependent variable values (F_P, T_p, LR, I and EA) provided by each junior shin guard. Baseline data were not collected for the adult experiment in order to ensure no damage would occur to the adult leg form and force transducer at the higher, adult impact energy levels.

Pilot Study

The purpose of the pilot study was to ensure that all equipment was working properly and to provide some preliminary sample data. The National Instrument compression force transducer used in the experiment can record a maximum force of 8896.4N. The force transducer was calibrated to obtain a conversion factor between volts recorded by the transducer and force displayed in LabVIEW. The manufacturer of the compression force transducer supplied a conversion factor of 909.51N/V. A known mass was then placed on the transducer to confirm the conversion factor. Preliminary testing was conducted on a used adult shin guard, in order to ensure that no drop height in the experiment would damage the leg forms or force transducer by reaching the maximum force. Impacts delivered to a used adult shin guard, from a maximum possible drop height of 1.600m, resulted in peak force values below the maximum value of 8896.4 N. The drop heights used in both the junior and adult experiments were also determined through impact testing of used shin guards. Used shin guards were impacted from increasing drop heights until changes in the force-time curves began to change significantly. As the drop heights increased, changes in the force-time curves appeared to indicate that the used junior shin guard became harder at 0.200m and the used adult shin guard became harder at 0.700m. These changes in the force-time curves were therefore believed to be indicative of material damage. A maximum drop height was then set at 0.150 m for the junior shin guards and 0.60 m for the adult shin guards.

Validity and Reliability

For both experiments to be valid, the experimenter ensured that the apparatus measured what it was intended to measure. Although there are many types of validity, not all types applied to this particular experiment. Compression force transducers are known to be valid instruments for measuring compressive forces, however, in order to ensure that the force transducer was indeed measuring force accurately, the criterion related validity was examined. The known mass used to confirm the conversion factor therefore also confirmed the criterion related validity.

For both experiments to be reliable, the experimenter examined if the subjects and apparatus produced the same results every time the test was administered. To verify subject reliability, coefficients of variation values were evaluated for each block of impact energy data. Low coefficients of variation (under 10%) were considered to be indicative of subject reliability. To verify the apparatus reliability, a test-retest comparison was performed using the data from the experiments and data collected after the completion of the experiments. In both the junior and adult experiments, the initial impact condition delivered to each location of every shin guard was repeated after the experiment. The two sets of data for every shin guard were then compared to determine apparatus reliability. A two-tailed t-test with a significance level set at $p<0.05$ was calculated for any given two sets of data. The purpose of this statistical procedure was to ensure that a specimen produced reliable results under the same experimental conditions on separate occasions. Failure to reject the null hypothesis of no significant differences between the means of the two data sets was therefore indicative of apparatus reliability.

General Statistical Analysis

Although the knee and tibia sections of each shin guard were physically joined together, functionally each section was independent from the other. Therefore, data collected at the tibia and data collected at the knee were analyzed independently for both the junior and adult experiments. Five separate analyses of variance (ANOVA) were performed in Statistica for each of the five dependent variables (F_p, T_p, LR, I and EA) in order to assess any main effects of shin guard or interaction effects of shin guard and impact energy. The level of significance of the calculated F ratio was set at $p<0.05$. Although the dependent variables were not considered independent from each other, a multivariate analysis of variance (MANOVA) was not performed for the data obtained in the experiment. A MANOVA procedure will tend to optimize the separation between the five separate ANOVAs, and will often weight each dependent variable differently in order to maximize that separation. Even though a benefit to performing the MANOVA procedure is to decrease the likelihood of a type I error, this becomes more of a concern as the number of dependent variables increases. In this experiment, only five dependent variables were used and therefore it was not as much of a concern. Weighting one dependent variable more heavily than the other may obscure the true nature of the results obtained in the experiment and therefore may result in erroneous conclusions. It is for this reason that five separate ANOVA procedures for each dependent variable were chosen over one MANOVA procedure.

Statistical Analysis (Junior Experiment)

The experimental design for the junior experiment consisted of 2 factors and 5 dependent variable measures (F_p, T_p, L_R, I, and EA) for two independent impact locations (knee and tibia). The two factors included; shin guard (A_1, ..., A_5) and impact energy level (B_1, B_2, B_3). Junior shin guards were labeled as JRT1 to JRT5 for the tibia location and JRK1 to JRK5 for the knee location. The impact energies delivered in the junior experiment were labeled as LOW for the 3.23 J condition, MED for the 4.07 J condition and HIGH for the 4.88 J condition. For either location, the two factors (A and B) manipulated in the experiment were considered to be categorical. Shin guard (factor A) was considered to be a between-subjects measure, whereas the impact energy level (factor B) was considered to be a within-subject measure for each shin guard. Each shin guard was therefore tested at each level of factor B for two independent locations.

Statistical Analysis (Adult Experiment)

The experimental design for the adult experiment consisted of 2 factors and 5 dependent measures (F_p, T_p, L_R, I, and EA) for two independent impact locations (knee and tibia). The two factors included; shin guard (A_1, ..., A_5) and impact energy level (B_1, B_2, B_3). Adult shin guards were labeled as AT1 to AT14 for the tibia location and AK1 to AK14 for the knee location. The impact energies delivered in the adult experiment were labeled as LOW for the 6.47 J condition, MED for the 12.9 J condition and HIGH for the 19.4 J condition. For either location, the two factors (A and B) manipulated in the experiment were considered to be categorical. Shin guard (factor A) was considered to be a between-subjects measure, whereas the impact energy level (factor B) was considered to be a within-subject measure for each shin guard. Each shin guard was therefore tested at each level of factor B for two independent locations. In the adult experiment, Tukey's HSD *post hoc* comparisons were performed to determine the exact source of statistically significant differences in the interaction effects of shin guard x impact energy and the main effects of shin guard at both the tibia and knee locations.

Hypotheses for Junior Experiment (at both the Knee and Tibia Locations)

Null Hypothesis (H_{o1}): No statistically significant differences will exist in the dependent variables due to a main effect of one factor.

Null Hypothesis (H_{o1}): No statistically significant interactions will exist between the two factors (shin guard and impact energy level).

Alternative Hypothesis (H_{a1}): A main effect of shin guard will exist. Therefore, regardless of the impact energy level, differences will exist in the dependent variables based solely on the shin guard impacted. *(Main effect of A)*

Alternative Hypothesis (H_{a2}): A main effect of impact energy level will exist. Therefore, regardless of the shin guard, differences will exist in the dependent variables based solely on the impact energy level delivered. *(Main effect of B)*

Alternative Hypothesis (H_{a3}): An interaction effect of shin guard and impact energy level will exist. Therefore any variation in the dependent variables due to impact energy level will depend on the shin guard being tested.
(Interaction effect of A x B)

Alternative Hypothesis (H_{a4}): An interaction effect of impact energy level and impact location will exist. Therefore any variation in the dependent variables due to the impact location will depend on what level of impact energy is being delivered.

Hypotheses for Adult Experiment (at both the Knee and Tibia Locations)

Null Hypothesis (H_{o1}): No statistically significant differences will exist in the dependent variables due to a main effect of one factor.

Null Hypothesis (H_{o1}): No statistically significant interactions will exist between the two factors (shin guard and impact energy level).

Alternative Hypothesis (H_{a1}): A main effect of shin guard will exist. Therefore, regardless of the impact energy level, differences will exist in the dependent variables based solely on the shin guard impacted. *(Main effect of A)*

Alternative Hypothesis (H_{a2}): A main effect of impact energy level will exist. Therefore, regardless of the shin guard, differences will exist in the dependent variables based solely on the impact energy level delivered. *(Main effect of B)*

Alternative Hypothesis (H_{a3}): An interaction effect of shin guard and impact energy level will exist. Therefore any variation in the dependent variables due to impact energy level will depend on the shin guard being tested. *(Interaction effect of A x B)*

Alternative Hypothesis (H_{a4}): An interaction effect of impact energy level and impact location will exist. Therefore any variation in the dependent variables due to the impact location will depend on what level of impact energy is being delivered.

Chapter 4

Results

Before any statistical analysis was performed on the data obtained during this experiment, it was important to determine if the apparatus and subjects were reliable. The intended statistical procedure for the experiment was a series of analyses of variance. In the case of an ANOVA, data demonstrating deterioration would violate two of the assumptions required to perform the statistical procedure. Data demonstrating damage would violate the assumption of homogeneity of variance and the assumption of independent observations. Therefore, the presence of material damage in a group of data necessitated that group of data's exclusion from any statistical analysis. An in depth evaluation of the data was performed in order to assess material damage that may have been sustained during the experiment. A summary of the evaluation is displayed in Figure 5.

Reliability Results.

As stated in the methods section, a two-tailed t-test was calculated for the initial and retest conditions delivered, for both locations of every shin guard (for each dependent variable) in the junior and adult experiments. The t-test results obtained for the junior and adult experiments are displayed in Tables 3 and 4 respectively. Conditions in which the t-tests failed to reject the null hypothesis (represented by "F") of no statistically significant difference between the means of both sets of data, indicated apparatus and subject reliability. Conditions in which

Figure 5. Summary of Reliability Assessment (Junior & Adult Experiments).

STEP 1 (Initial & retest conditions)

Initial 12 drops (All DVs) ↘ ↘

Restest 12 drops (All DVs) ↙ ↙

Two-tailed t-test Comparisons
($p < 0.05$)

↙ ↙

Fail to reject null
↓
↓
Data for location accepted
for statistical analyses

↘ ↘

Reject null

↙ ↙

% Difference
< 7%
↙
↙
Data for location accepted
for statistical analyses

↘ ↘

% Difference
> 7%
↘
↘
Data for location rejected
for statistical analyses

STEP 2 (All conditions in experiment)

3 conditions at one impact location
graphed in order they were delivered
(F_p only)
↓
↓
CoVar determined for graphs
displaying increase in F_p values

↙ ↙

CoVar < 2.5%
↙
↙
Data for condition accepted
for statistical analyses

↘ ↘

CoVar > 2.5%
↘
↘
Data for condition rejected
for statistical analyses

Table 3. T-test Comparisons for initial-retest data (Junior Experiment).

GUARD	Peak	% Diff	TtoPeak	% Diff	LdRate	% Diff	Impulse	% Diff
JRK1M	R*	11.3**	R*	-4.4	R*	16.5**	R*	-1.2
JRT1M	R*	7.9**	R*	-2.8	R*	9.4**	R*	3.6
JRK2L	F	-0.5	R*	-2.4	F	-0.2	R*	-3.2
JRT2H	R*	-2.4	F	-1.3	R*	-9.9	R*	-5.5
JRK3L	R*	-4.3	R*	3.4	R*	-9.4	R*	-0.5
JRT3L	R*	9.6**	F	-1.2	R*	-2.4	R*	2.8
JRK4M	R*	12.1**	R*	10	R*	-14.3	R*	1.0
JRT4L	R*	129.5**	R*	-13.9**	R*	941.1**	R*	-2.2
JRK5M	R*	-35.5	R*	11.8	R*	-84.0	R*	-5.6
JRT5H	R*	42.3**	R*	-7.9**	R*	123.3**	R*	-2.9

R=Reject null=statistical difference in means ($p<0.05$)
F=Fail to reject null=statistically no difference in means ($p<0.05$)
% Difference=percent difference between initial and retest means
*** Rejected from statistical analyses based on significant t-test criterion**
****Rejected from statistical analyses based on > 7% difference criterion**

Table 4. T-test Comparisons for initial-retest data (Adult Experiment).

GUARD	Peak	%Diff	TtoPeak	%Diff	LdRate	%Diff	Impulse	%Diff
A1KL	R*	1.2	R*	5.3	F	-3.7	R*	0.4
A1TM	R*	6.6	R*	-1.8	F	2.5	R*	1.7
A2KL	F	0.0	R*	0.8	R*	9.3**	R*	2.4
A2TL	R*	-9.6	R*	-19.3**	F	-3.6	R*	3
A3KL	R*	-7.8	R*	10.2	F	1	R*	-6.6
A3TM	R*	-5.0	R*	-11.7**	F	-0.2	R*	1.1
A4KL	R*	-12.5	F	3.3	F	-1.9	R*	-2.9
A4TM	R*	-9.4	R*	-5.6	R*	-11.8	R*	1.6
A5KH	F	-0.4	F	-.09	R*	17.6**	R*	-1.2
A5TM	R*	-3.3	R*	-12.1**	R*	-6.2	R*	1.1
A6KH	R*	2.9	R*	-2.1	R*	26.4**	F	-0.2
A6TM	R*	-9.9	R*	-4.0	R*	-3.6	R*	2
A7KH	R*	4.4	R*	-2.6	R*	-8.6	F	-0.6
A7TL	R*	-1.0	R*	6.4	R*	34.7**	R*	1
A8KL	R*	-3.0	R*	8.4	R*	-7.8	R*	0.9
A8TM	R*	19.1**	F	6.1	R*	-20.6	R*	0.9
A9KL	R*	-1.6	F	3.1	R*	-12.4	R*	1.5
A9TL	R*	-6.4	R*	-2.3	R*	36.2**	R*	1.5
A10KM	R*	-4.3	F	-0.8	R*	3.6	R*	-2.8
A10TM	R*	13.9**	F	1.5	R*	13.4**	R*	1
A11KM	R*	-1.7	R*	3.3	F	-1.4	R*	-1
A11TL	R*	2.1	R*	-3.4	R*	-9.7	R*	0.4
A12KH	R*	5.6	R*	-2.6	R*	1.8	F	-0.3
A12TL	F	0.7	R*	1.6	R*	-18.2	F	0.1
A13KM	R*	-1.9	R*	7.8	R*	-7.3	R*	-1.1
A13TH	R*	15.2**	R*	-6.7	R*	70.8**	R*	-1.6
A14KL	R*	-4.5	R*	1.9	R*	-25.4	R*	1.9
A14TL	F	0.2	R*	6.2	R*	-4.7	R*	3.4

R=Reject null=statistical difference in means ($p<0.05$)
F=Fail to reject null=statistically no difference in means ($p<0.05$)
% Difference=percent difference between initial and retest means
*** Rejected from statistical analyses based on significant t-test criterion**
****Rejected from statistical analyses based on >7% difference criterion**

the t-test rejected the null hypothesis (represented by "R") did not necessarily indicate apparatus unreliability, but very probably represented shin guard unreliability. The statistically significant differences in the means may have been due to apparatus unreliability, but most likely were due to damage or deterioration present in the shin guard material. Therefore, any condition in which the t-test rejected the null hypothesis was considered to represent damaged material. However, a particular shin guard location could not be removed from the statistical analysis based solely on the t-test comparisons. The means, standard deviations and coefficients of variation for each condition of all shin guards, in both the junior and adult experiments, are displayed in Appendices J, K, L, and M respectively. It was noted that the variability in many conditions, for both the junior and adult experiments, was relatively low. Therefore, any small change in the mean of the retest condition when compared to the initial condition resulted in a statistically significant difference and subsequently resulted in the rejection of the null hypothesis in a t-test comparison. Although the change was statistically significant, it may not have been considered a meaningful change. In order to ensure that the t-test analyses were not too conservative in determining material damage, percent changes between the two means (in all dependent variables) were also investigated.

The percent change between the means (for all dependent variables) of the initial conditions and the retest conditions at each location (for all shin guards) are displayed in Table 3 for the junior experiment and Table 4 for the adult experiment. Any percent change greater than 7% (in any dependent variable) was considered a meaningful change in the means, and therefore served as a second criterion to determine material damage. It is important to note that more emphasis was placed on the peak force (F_p) dependent variable when determining material damage. Time to peak values were very small in magnitude, therefore eliminating data based on a percentage change of such a small magnitude might not have accurately indicated material damage. Any change in the force-time curve due to material damage might have also skewed the loading rate, impulse, and energy absorption values, and also might not have accurately indicated material damage. Therefore, if the percent change between the initial condition and the retest condition (in F_p only) was greater than 7%, data from that impact location was excluded from any statistical analysis. It is also important to note, that any condition that resulted in a change in means (in F_p only) in the direction that indicated a superior performance in the retest condition, was not rejected on the above criterion. For example, if the mean peak force for a particular shin guard decreased between the initial and retest conditions, indicating a superior performance at the retest condition, that shin guard location was not rejected from the statistical analysis. Based on the above criterion, Table 3 revealed that junior shin guards JRT1, JRT3, JRK4, JRT4, and JRT5 displayed material damage and were therefore excluded from any statistical analyses. The percent differences reflecting material damage between the initial and the retest conditions, in the junior experiment, ranged from 7.9 to 129.5%. Junior shin guards JRK2, JRT2, JRK3, and JRK5 actually indicated a superior performance in the retest condition. Based on the above criterion, Table 4 revealed that adult shin guards AT8, AT10 and AT13 were excluded at the tibia location and no adult shin guards were rejected at the knee location. Although this criterion of 7% change in the means of initial and retest conditions was useful in excluding shin guard locations that may have shown material damage, it was not the only criterion used to exclude data. In order to gain a further understanding of all material damage that may have been sustained, peak force values for all 15 drops, for the three impact energy levels (in the order they were delivered during the experiment) were investigated for each of the junior and adult shin guards, at both the tibia and knee locations.

The F_p values, for all 15 drops at each impact energy condition, are located in Appendices F and G for the junior shin guards and Appendices H and I for the adult shin guards. Ideally, the F_p values for every block of 15 drops should remain relatively flat, indicating consistent peak force recordings for repeated drops under one particular condition. Unfortunately, this was not the case in all conditions for the junior or adult experiments. It can be noted that in both the junior and adult experiments, some conditions displayed a gradual increase in F_p values throughout the block of 15 drops. This gradual increase in F_p values was considered to be indicative of material damage. As a result, a particular group of 15 drops that displayed a noticeable increase in F_p values was deemed to have sustained damage and was therefore unreliable data. Visual inspection of the graphs in Appendices F, G, H and I therefore helped to identify individual conditions that indicated material damage, which were then investigated further based on the coefficients of variation for that block of 15 drops. For all blocks of 15 drops that indicated material damage based on visual inspection in the junior experiment, the coefficients of variation in F_p ranged from 6.1 to 21.4% at the tibia location and 5.2 to 28.9% at the knee location. For all blocks of 15 drops that indicated material damage in the adult experiment, the coefficients of variation in F_p ranged from 2.6 to 14.7% at the tibia location and 2.6 to 5.4% at the knee location. The coefficient of variation of 2.5% in F_p was therefore set as the criterion value for determining additional unreliable or damaged material. Any block of 15 drops that had a coefficient of variation greater than 2.5% for F_p, was rejected from the statistical analyses. Therefore, specimens that were not rejected based on the t-test or percent difference in means between initial and retest conditions criteria, were also investigated at each condition based on the coefficient of variation criterion. Any conditions eliminated based on the coefficient of variation criterion are indicated in Appendices J and K for the junior shin guards and Appendices L and M for the adult shin guards. Summaries of accepted conditions for statistical analysis, based on the three criteria (t-test, percent difference between means and coefficient of variation) are listed for both locations (knee and tibia) in Table 5 for the junior experiment and Table 6 for the adult experiment. It is clear from Tables 5 and 6, that at any given location, some shin guard data were accepted for the three impact energy level conditions, some shin guard data were accepted for two impact energy level conditions, and some shin guard data were accepted only for one impact energy level condition.

Table 5. Summary of Accepted Conditions for the Junior Experiment.

TIBIA	LOW	MED	HIGH
JRT1	N	N	N
JRT2	A	A	N
JRT3	N	N	N
JRT4	N	N	N
JRT5	N	N	N

KNEE	LOW	MED	HIGH
JRK1	N	N	N
JRK2	N	N	N
JRK3	A	A	A
JRK4	N	N	N
JRK5	N	N	N

A= Accepted for statistical analyses
N= Not accepted for statistical analyses

Table 6. Summary of Accepted Conditions for the Adult Experiment.

TIBIA	LOW	MED	HIGH
AT1	A	N	N
AT2	N	N	N
AT3	A	A	A
AT4	A	A	A
AT5	A	A	A
AT6	A	A	A
AT7	A	A	A
AT8	N	N	N
AT9	A	N	N
AT10	N	N	N
AT11	A	N	N
AT12	N	N	N
AT13	N	N	N
AT14	A	N	N

KNEE	LOW	MED	HIGH
AK1	A	A	N
AK2	A	A	N
AK3	A	A	A
AK4	A	A	A
AK5	A	A	A
AK6	A	A	A
AK7	A	A	N
AK8	A	A	N
AK9	A	N	N
AK10	A	N	N
AK11	N	N	N
AK12	A	A	N
AK13	A	N	N
AK14	A	A	N

A= Accepted for statistical analyses
N= Not accepted for statistical analyses

Results (Junior Experiment)

The reliability results indicated material damage or subject unreliability in most of the junior data. As a result, many shin guards and conditions were eliminated from the statistical analyses at either of the two locations (see Table 5) in the junior experiment. Junior shin guard JRT2 was accepted for the first two impact energy levels and JRK3 was accepted for all three impact energy levels. As a result, not enough data were accepted to perform useful statistical analyses. However, although none of the data in the junior experiment underwent a set of ANOVAs for the dependent variables, the means (for each block of 12 drops) for each dependent variable, at each condition of every shin guard, are represented graphically in Figures 6, 7, 8, 9, and 10. Percentage difference in dependent variables between the baseline (double layer of foam) and all junior shin guards are listed in Table 7.

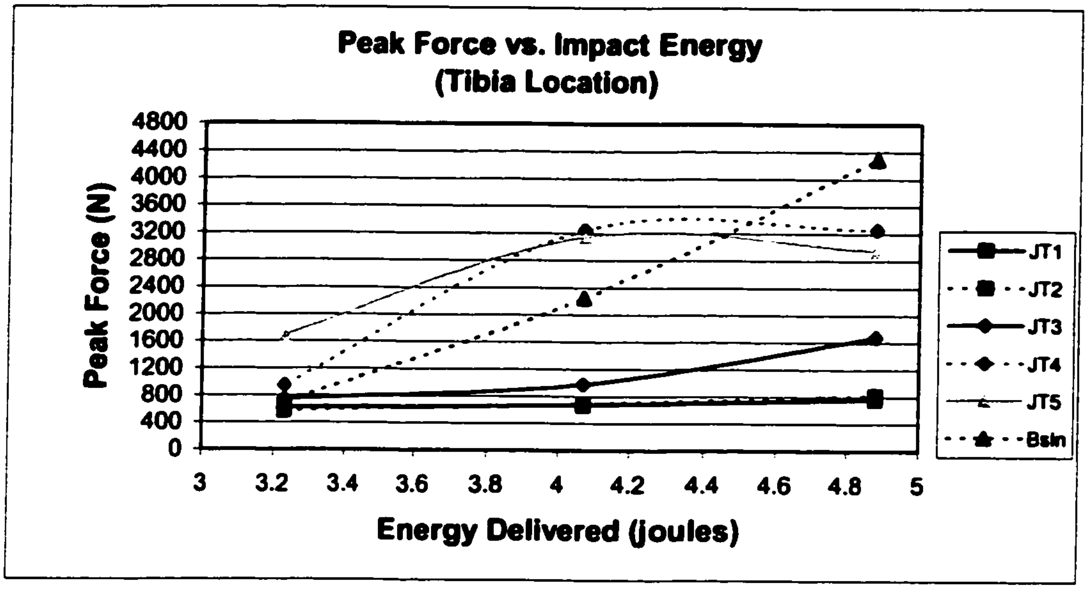
Table 7. Percentage Difference in Dependent Variables Between the Baseline Foam and All Junior Shin Guards.

Tibia Location		Peak Force	Time to Peak	Loading Rate	Impulse
ImpactE		(N/s)	(ms)	(N/s)	I (N-s)
LOW 3.23j	JRT1	-10.55	-26.07	-0.88	20.36
	JRT2	-17.29	-24.48	-3.40	19.49
	JRT3	7.40	-33.35	52.26	15.39
	JRT4	36.60	-34.57	9.02	20.08
	JRT5	144.12	-37.48	194.04	21.97
MED 4.07j	JRT1	-70.14	12.17	-92.22	14.04
	JRT2	-69.29	0.67	-92.20	15.07
	JRT3	-56.68	-12.04	-87.75	13.38
	JRT4	44.16	-22.73	98.32	12.06
	JRT5	39.68	-23.23	81.72	11.29
HIGH 4.88j	JRT1	-82.22	0.99	-97.74	2.49
	JRT2	-80.92	0.54	-97.15	8.65
	JRT3	-60.93	-30.63	-94.86	-0.09
	JRT4	-24.39	-30.42	-42.87	-8.37
	JRT5	-31.25	-32.82	-56.40	-0.73

Knee Location		Peak Force	Time to Peak	Loading Rate	Impulse
ImpactE		(N/s)	(ms)	(N/s)	I (N-s)
LOW 3.23j	JRK1	-19.40	-19.54	-35.21	22.71
	JRK2	-14.72	-11.19	-33.18	27.41
	JRK3	-17.80	-27.55	-4.28	10.70
	JRK4	-30.01	-9.80	-41.45	24.11
	JRK5	-19.90	-12.17	-40.59	22.92
MED 4.07j	JRK1	-70.32	27.99	-94.80	18.66
	JRK2	-67.98	15.74	-94.34	17.07
	JRK3	-72.68	12.67	-93.26	5.92
	JRK4	-73.02	21.36	-95.36	16.74
	JRK5	-46.25	12.37	-91.54	18.46
HIGH 4.88j	JRK1	-71.25	-1.58	-96.78	4.99
	JRK2	-78.09	7.92	-97.79	5.66
	JRK3	-83.48	-6.66	-97.76	-5.52
	JRK4	-67.83	-4.45	-97.28	3.25
	JRK5	-39.99	-11.00	-57.98	0.89

(-)=%Decrease from Baseline Foam Values
(+)=%Increase from Baseline Foam Values

Figure 6. Mean Peak Force Values for All Junior Shin Guards, at All Three Impact Energy Levels (Tibia and Knee Locations).



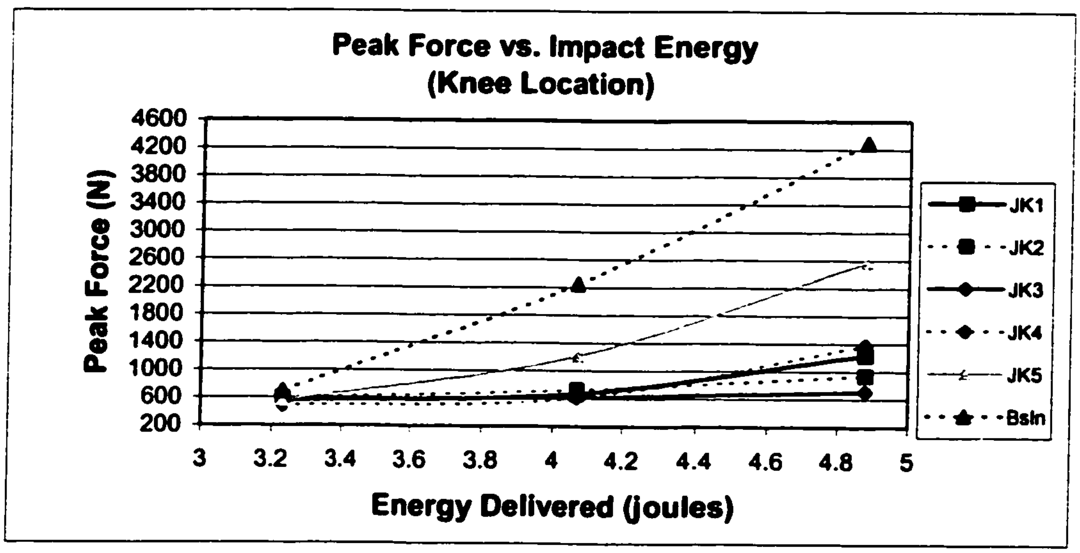
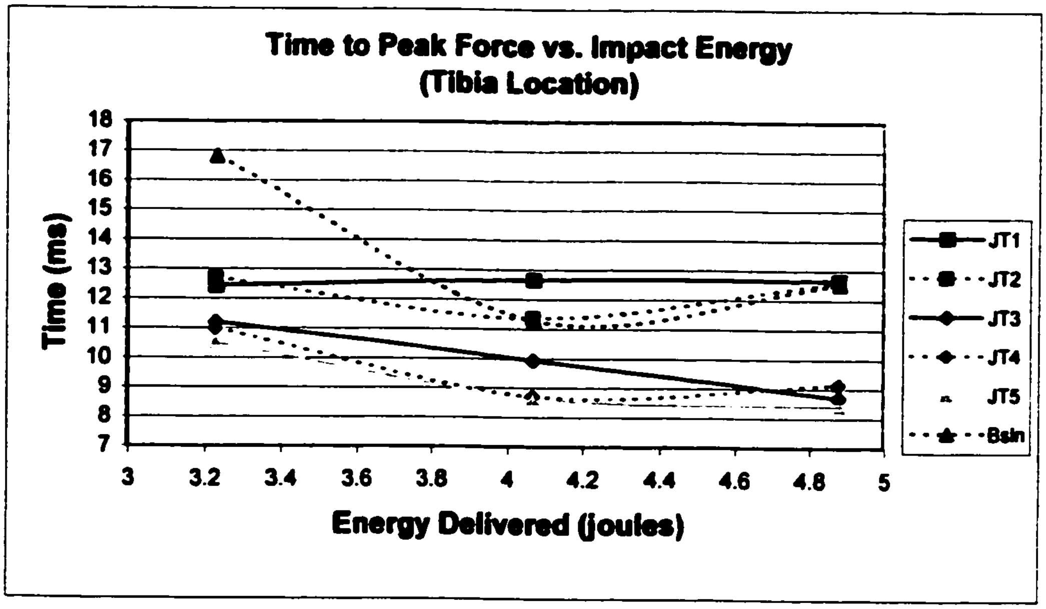


Figure 7. Mean Time to Peak Force Values for All Junior Shin Guards, at All Three Impact Energy Levels (Tibia and Knee Locations).



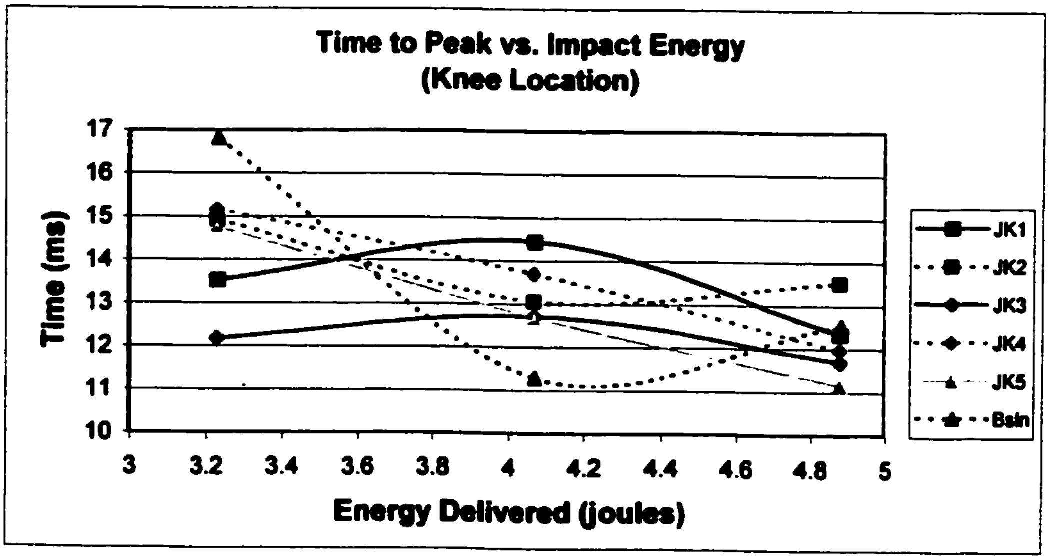
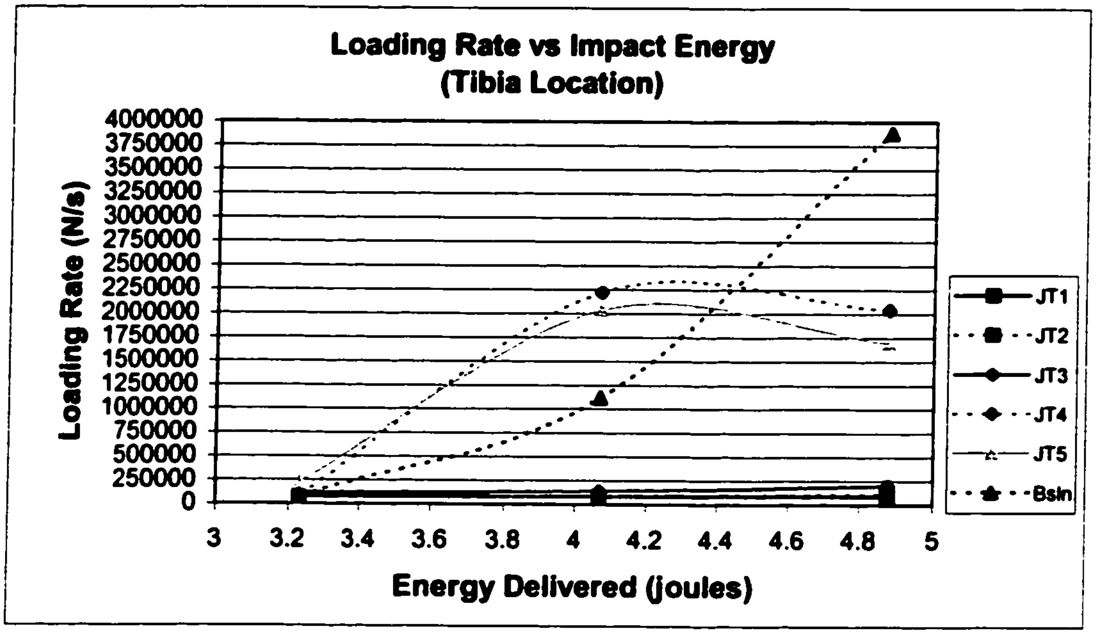


Figure 8. Mean Loading Rate Values for All Junior Shin Guards, at All Three Impact Energy Levels (Tibia and Knee Locations).



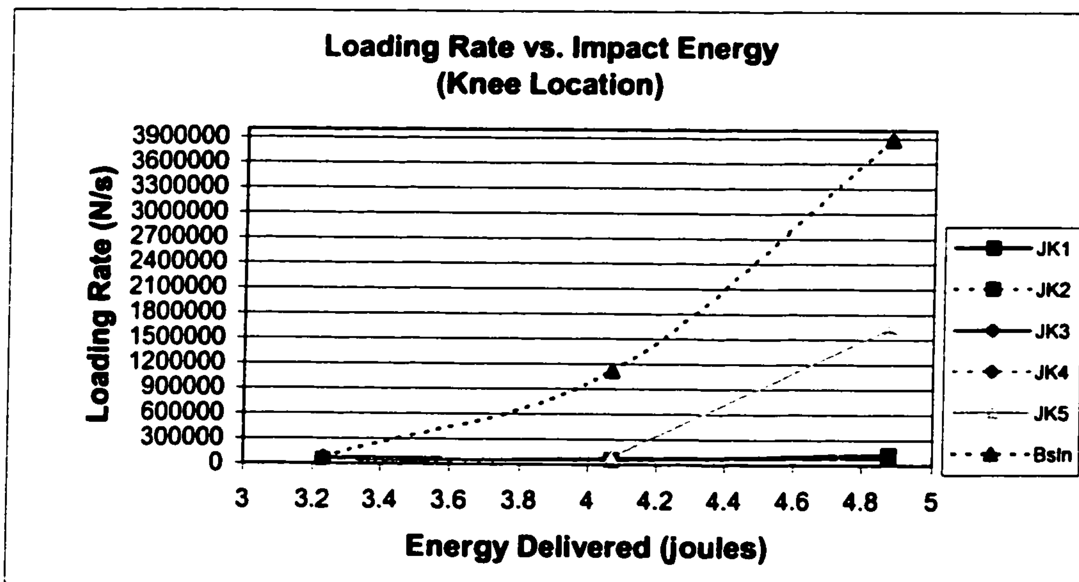
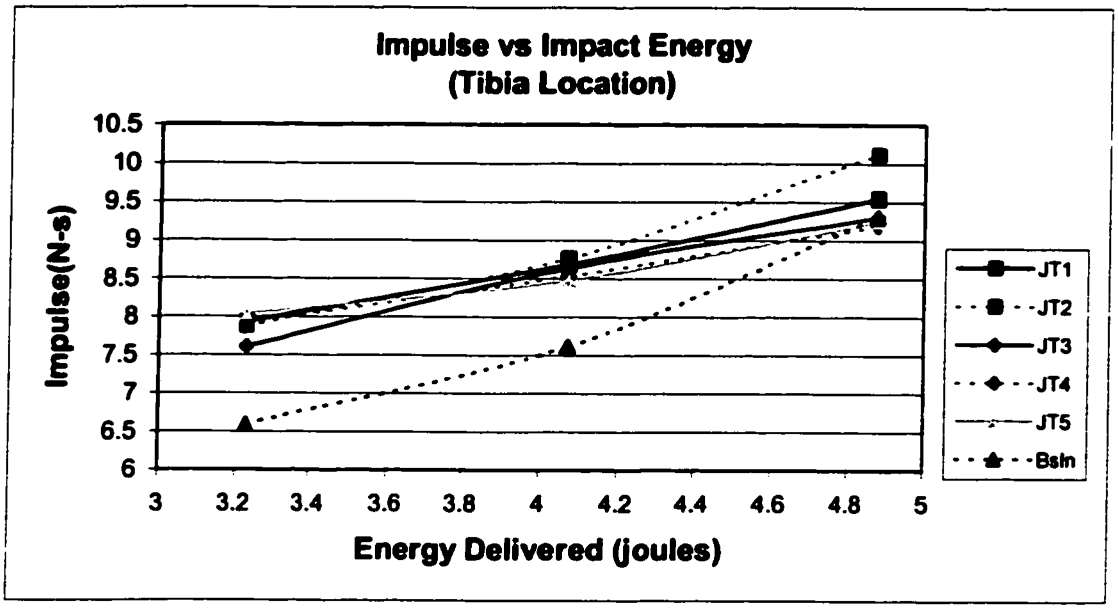


Figure 9. Mean Impulse Values for All Junior Shin Guards, at All Three Impact Energy Levels (Tibia and Knee Locations).



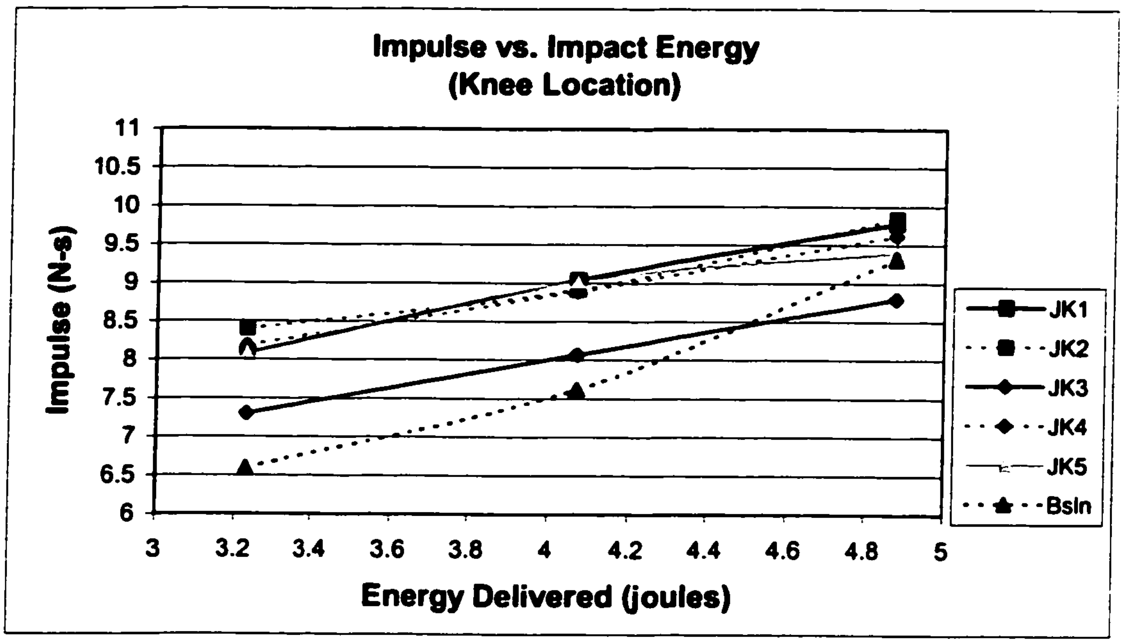
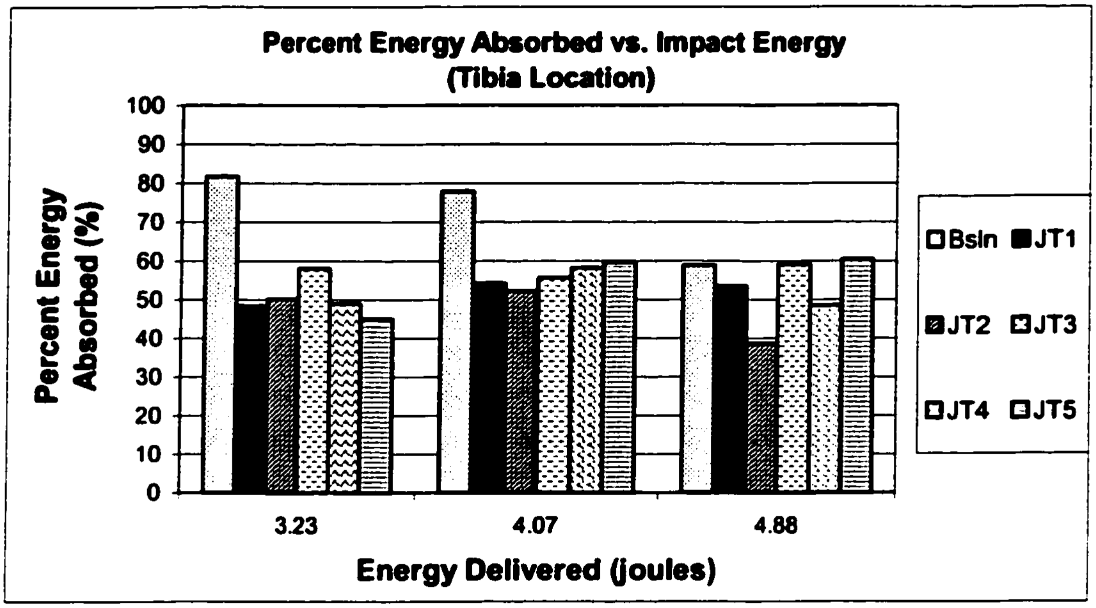
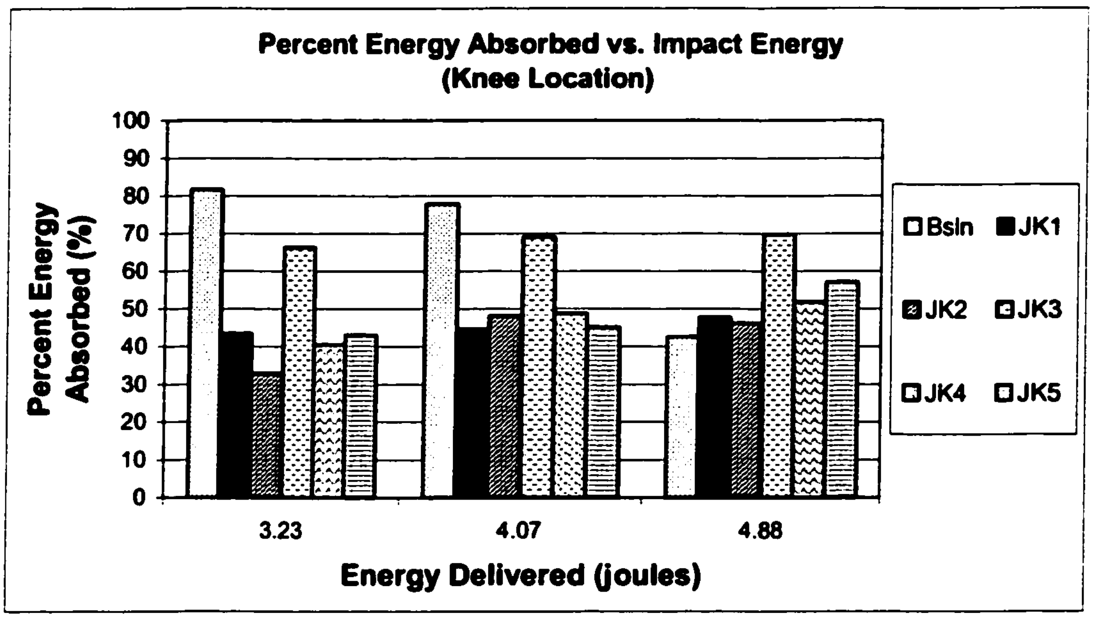


Figure 10. Mean Percent Energy Absorption Values for All Junior Shin Guards, at All Three Impact Energy Levels (Tibia and Knee Locations).





Results (Adult Experiment)

The reliability results indicated material damage or subject unreliability in some of the adult data. As a result, some shin guards and conditions were eliminated from the statistical analysis at either of the two locations (see Table 6) in the adult experiment. Two sets, of five analyses of variance, were conducted at the tibia location. The first set of five ANOVAs (labeled AT-ANOVA1) consisted of an ANOVA for each of the five dependent variables (F_p, T_p, LR, I and EA) for shin guards that were accepted for all three impact energy level conditions (LOW, MED, HIGH). The adult shin guards included in the five AT-ANOVA1 analyses were AT3, AT4, AT5, AT6, and AT7. The results of the five AT-ANOVA1 analyses revealed significant interaction effects ($p<0.05$) of shin guard x impact energy level for all five dependent variables (Table 8). The graphical representation of the interaction effects for the five AT-ANOVA1 analyses, are displayed in Appendix N. Unfortunately at the tibia section, there were not any shin guards that were accepted for two impact energy levels. Therefore, the second set of five ANOVAs (labeled AT-ANOVA2) at the tibia location consisted of an ANOVA for each of the five dependent variables for shin guards that were accepted only at one impact energy level condition (LOW). The adult shin guards included in the five AT-ANOVA2 analyses were AT1, AT3, AT4, AT5, AT6, AT7, AT9, AT11, and AT14. The results of the five AT-ANOVA2 analyses revealed significant main effects ($p<0.05$) of shin guard for all five dependent variables (Table 9). The graphical representation of the main effects for the five AT-ANOVA2 analyses, are displayed in Appendix O. In addition, the mean values (for each block of 12 drops) for all five dependent variables for all conditions delivered to the tibia location are displayed graphically in Figures, 11, 12, 13, 14 and 15.

The results of *post hoc* comparisons at the tibia location are listed in Appendices S and T. The results indicated that the analyses including all three impact energy levels (AT-ANOVA1) revealed significant interaction effects of shin guard and impact energy level for all five of the dependent variables (Table 8). *Post Hoc* comparisons in Appendix S revealed that there were several significant comparisons resulting in the statistically significant interaction effects for each of the dependent variables. Upon further investigation of the *post hoc* comparisons, it appeared that the F_p, T_p and LR dependent variables were the most effective at identifying significant differences between the shin guards.

The results indicated that the analyses including only the low impact energy level (AT-ANOVA2) revealed significant main effects of shin guard for all five of the dependent variables (Table 9). *Post Hoc* comparisons in Appendix T revealed that there were several significant comparisons resulting in the statistically significant main effects of shin guard for each of the dependent variables. Upon further investigation of the *post hoc* comparisons, it appeared that the F_p and LR dependent variables were the most effective at identifying significant differences between the shin guards.

Table 8. Analyses of Variance for Adult Shin Guards Accepted for All Three Impact Energy Levels at the Tibia Location (AT-ANOVA1).

Peak Force

Summary of all Effects; design: (at-anova1.sta) 1-GUARD, 2-PEAK						
	df Effect	*MS* Effect	*df* Error	*MS* Error	*F*	*p-level*
1	4	315533.2	55	92.9323	3395.302	0*
2	2	4067652	110	96.84409	42002.07	0*
1 x 2	8	8464.819	110	96.84409	87.40666	0*

Time to Peak

Summary of all Effects; design: (at-anova1.sta) 1-GUARD, 2-TIME						
	df Effect	*MS* Effect	*df* Error	*MS* Error	*F*	*p-level*
1	4	1.779348	55	0.096653	18.40958	1.19E-09*
2	2	45.26742	110	0.084993	532.5992	0*
1 x 2	8	7.874841	110	0.084993	92.65237	0*

Loading Rate

Summary of all Effects; design: (at-anova1.sta) 1-GUARD, 2-LDRT						
	df Effect	*MS* Effect	*df* Error	*MS* Error	*F*	*p-level*
1	4	1.85E+11	55	58332192	3175.721	0*
2	2	6.11E+11	110	54323184	11254.55	0*
1 x 2	8	2.81E+10	110	54323184	517.1132	0*

Impulse

Summary of all Effects; design: (at-anova1.sta) 1-GUARD, 2-IMPULSE						
	df Effect	*MS* Effect	*df* Error	*MS* Error	*F*	*p-level*
1	4	0.163642	55	0.01946	8.409076	2.29E-05*
2	2	919.9893	110	0.008483	108452	0*
1 x 2	8	0.084462	110	0.008483	9.956723	2.40E-10*

Energy Absorbed

Summary of all Effects; design: (at-anova1.sta) 1-GUARD, 2-EABSORB						
	df Effect	*MS* Effect	*df* Error	*MS* Error	*F*	*p-level*
1	4	0.564203	55	0.068932	8.184975	2.98E-05*
2	2	841.6725	110	0.030931	27211.34	0*
1 x 2	8	0.290725	110	0.030931	9.399172	8.07E-10*

*** Statisitcally Significant**

Table 9. Analyses of Variance for Adult Shin Guards Accepted for One Impact Energy Level at the Tibia Location (AT-ANOVA2).

Peak Force

Summary of all Effects; design: (at-anova2.sta) 1-GUARD						
	df Effect	*MS* Effect	*df* Error	*MS* Error	*F*	*p-level*
1	8	168399.9	99	50.26889	3349.982	0*

Time to Peak

Summary of all Effects; design: (at-anova2.sta) 1-GUARD						
	df Effect	*MS* Effect	*df* Error	*MS* Error	*F*	*p-level*
1	8	75.85501	99	0.954889	79.43858	0*

Loading Rate

Summary of all Effects; design: (at-anova2.sta) 1-GUARD						
	df Effect	*MS* Effect	*df* Error	*MS* Error	*F*	*p-level*
1	8	9.27E+09	99	27908082	332.2267	0*

Impulse

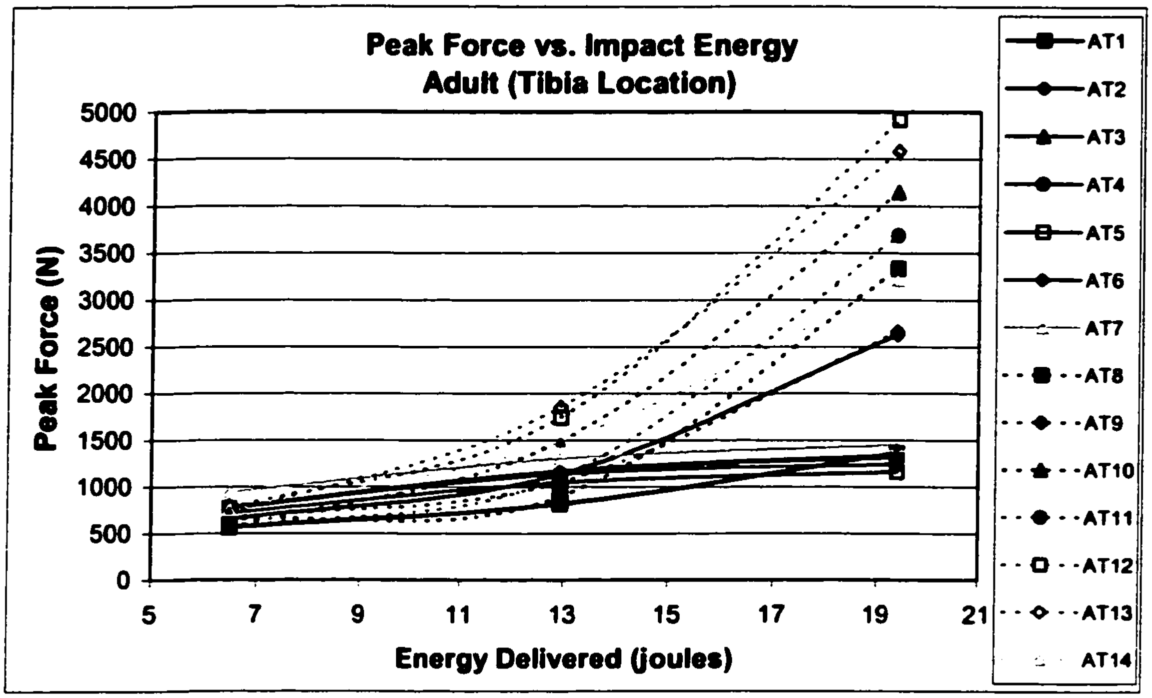
Summary of all Effects; design: (at-anova2.sta) 1-GUARD						
	df Effect	*MS* Effect	*df* Error	*MS* Error	*F*	*p-level*
1	8	0.375671	99	0.006276	59.85978	0*

Energy Absorbed

Summary of all Effects; design: (at-anova2.sta) 1-GUARD						
	df Effect	*MS* Effect	*df* Error	*MS* Error	*F*	*p-level*
1	8	0.727065	99	0.011896	61.11967	0*

*** Statistically Significant**

Figure 11. Mean Peak Force Values for All Adult Shin Guards, at All Three Impact Energy Levels (Tibia and Knee Locations).



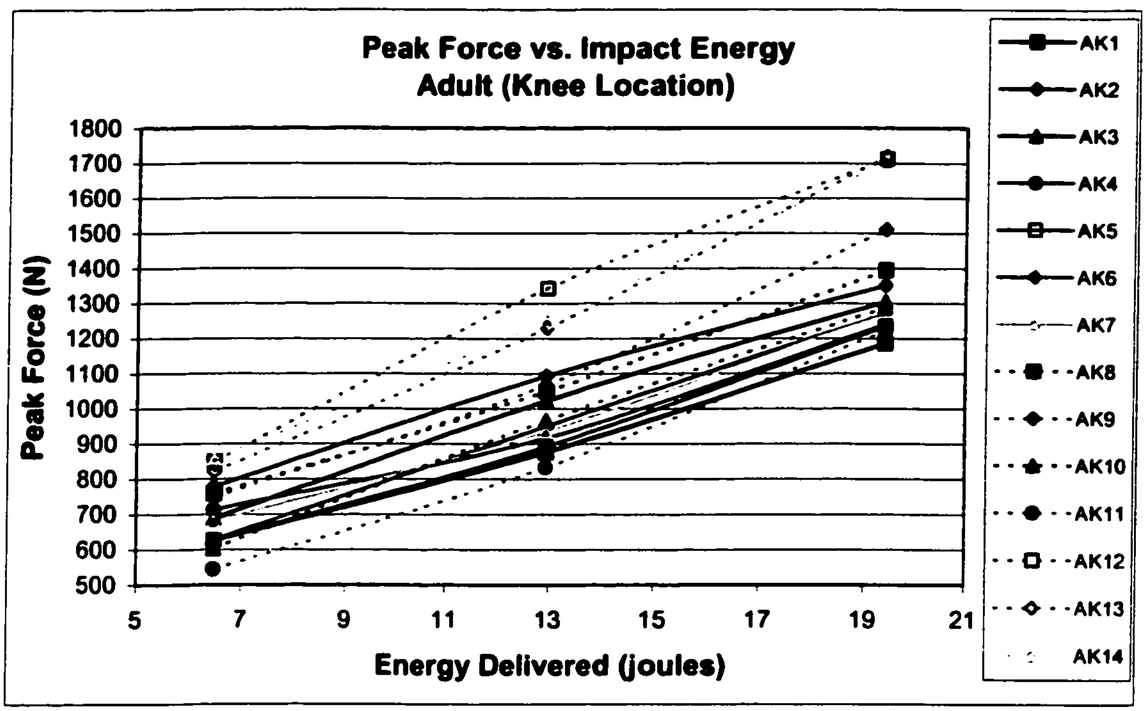
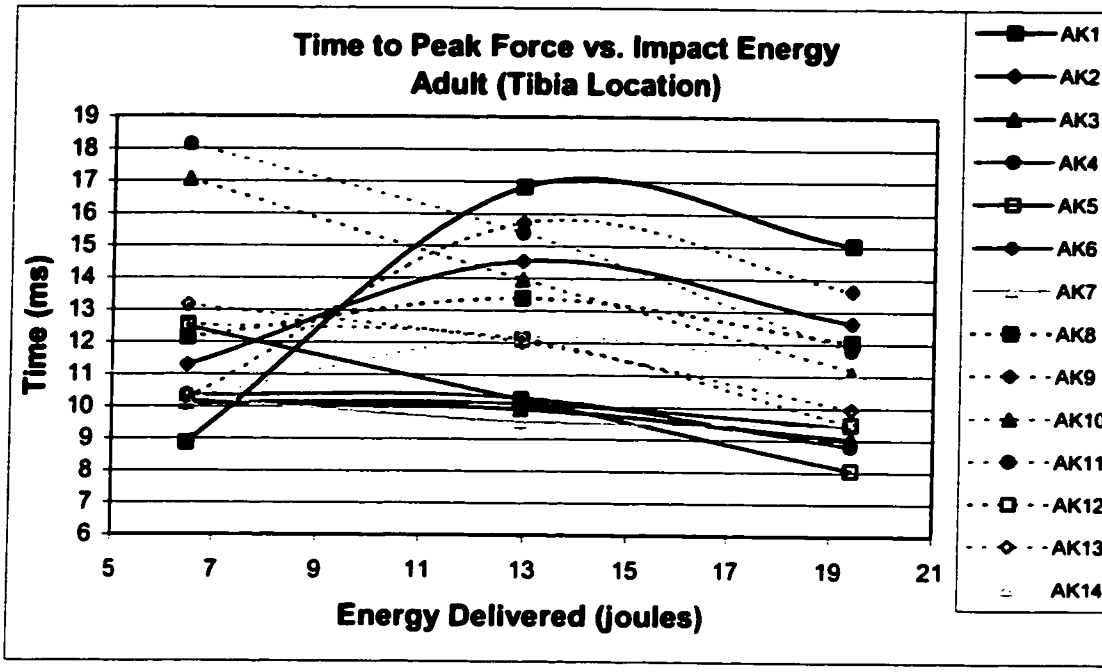


Figure 12. Mean Time to Peak Force Values for All Adult Shin Guards, at All Three Impact Energy Levels (Tibia and Knee Locations).



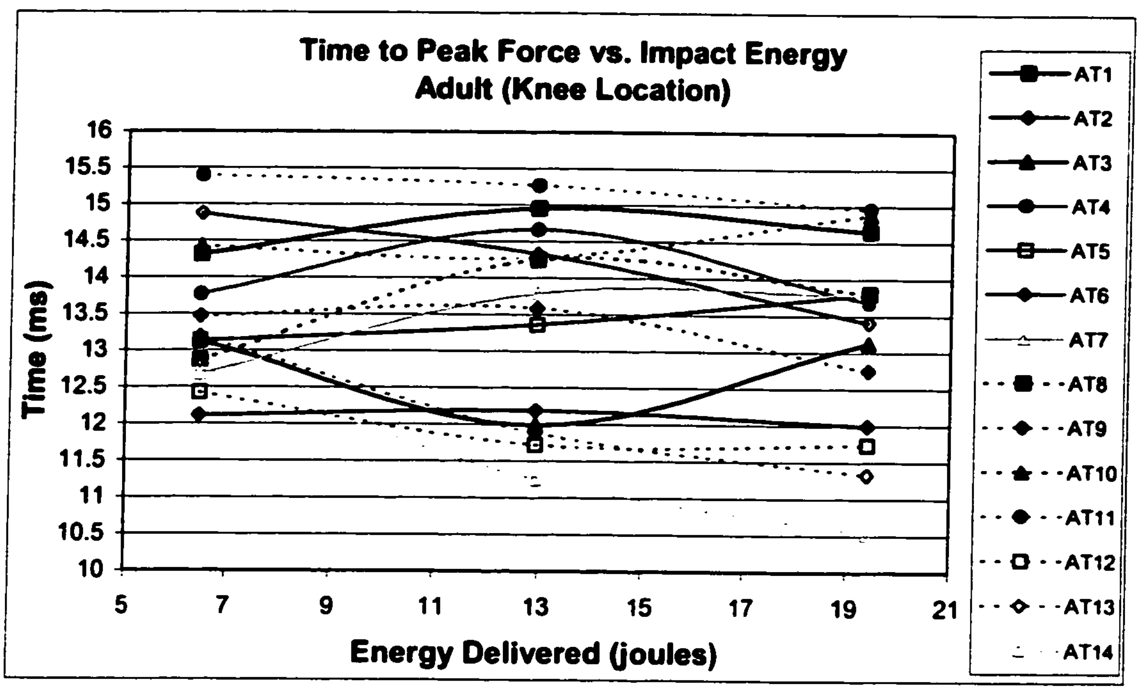
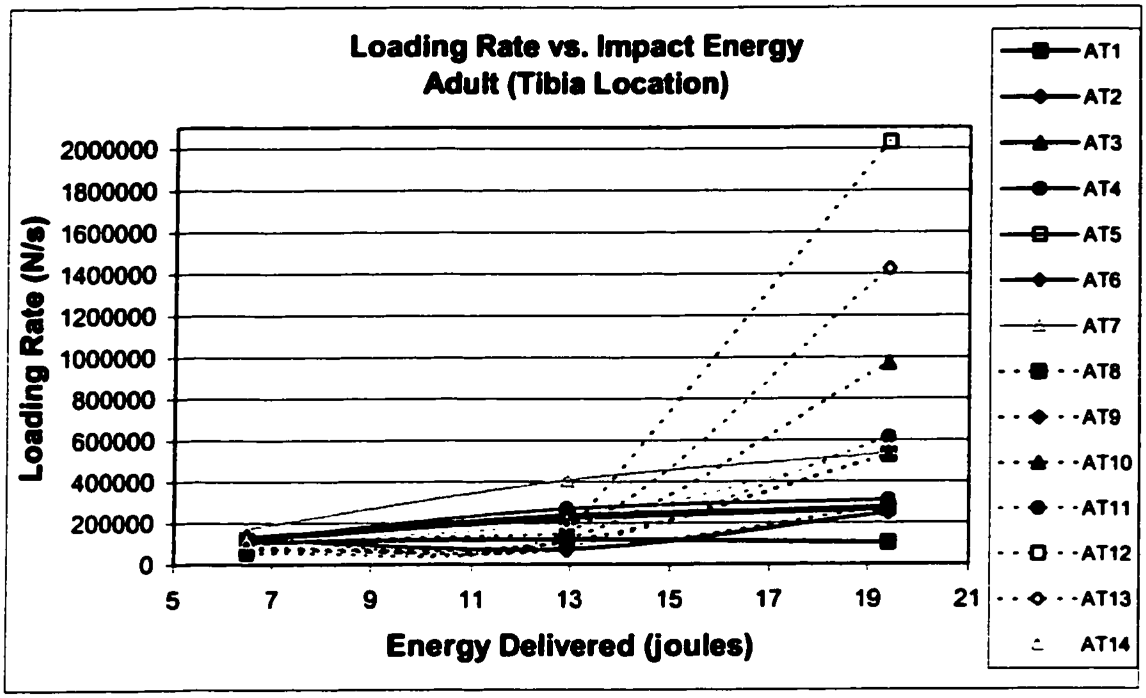


Figure 13. Mean Loading Rate Values for All Adult Shin Guards, at All Three Impact Energy Levels (Tibia and Knee Locations).



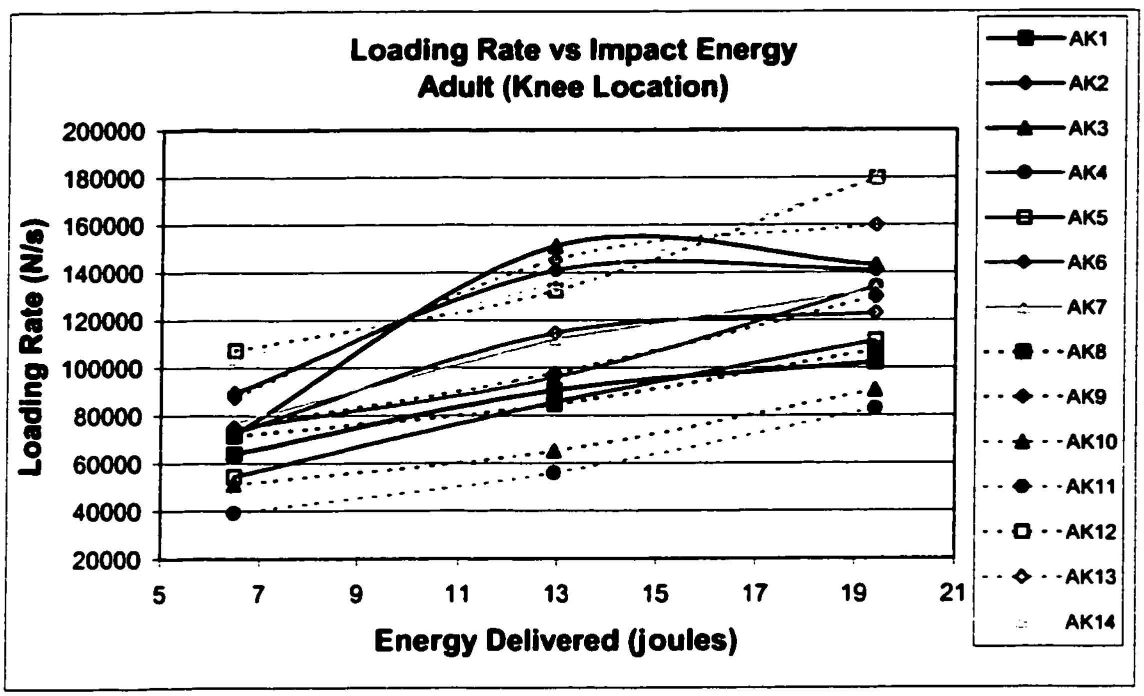
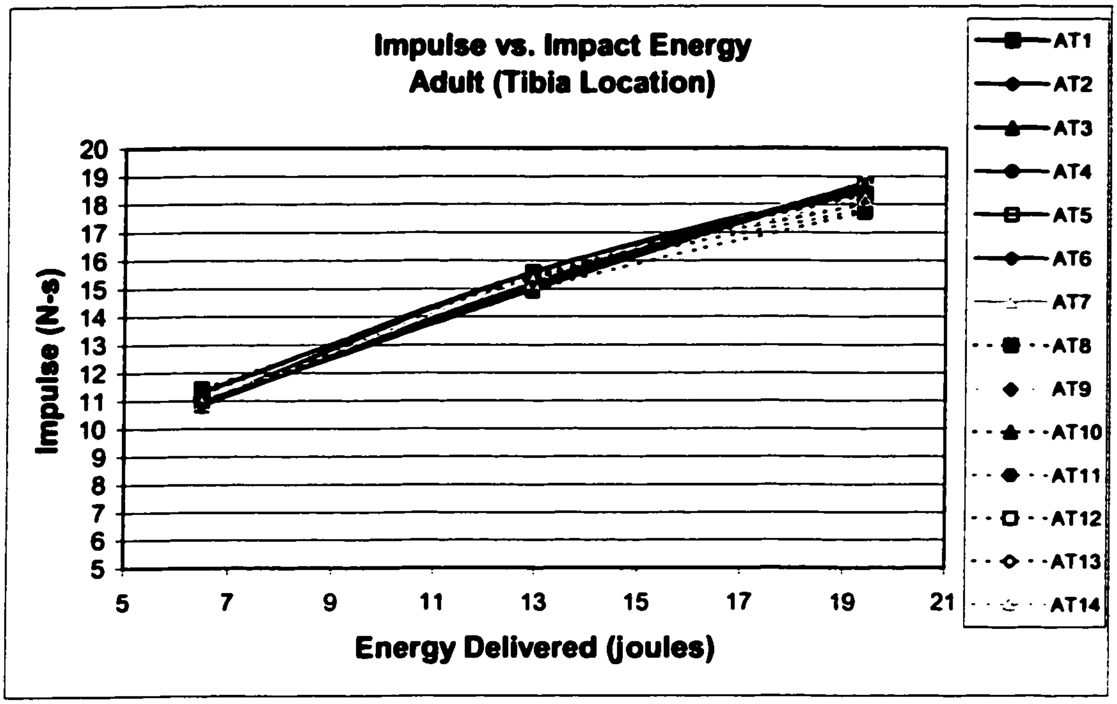


Figure 14. Mean Impulse Values for All Adult Shin Guards, at All Three Impact Energy Levels (Tibia and Knee Locations).



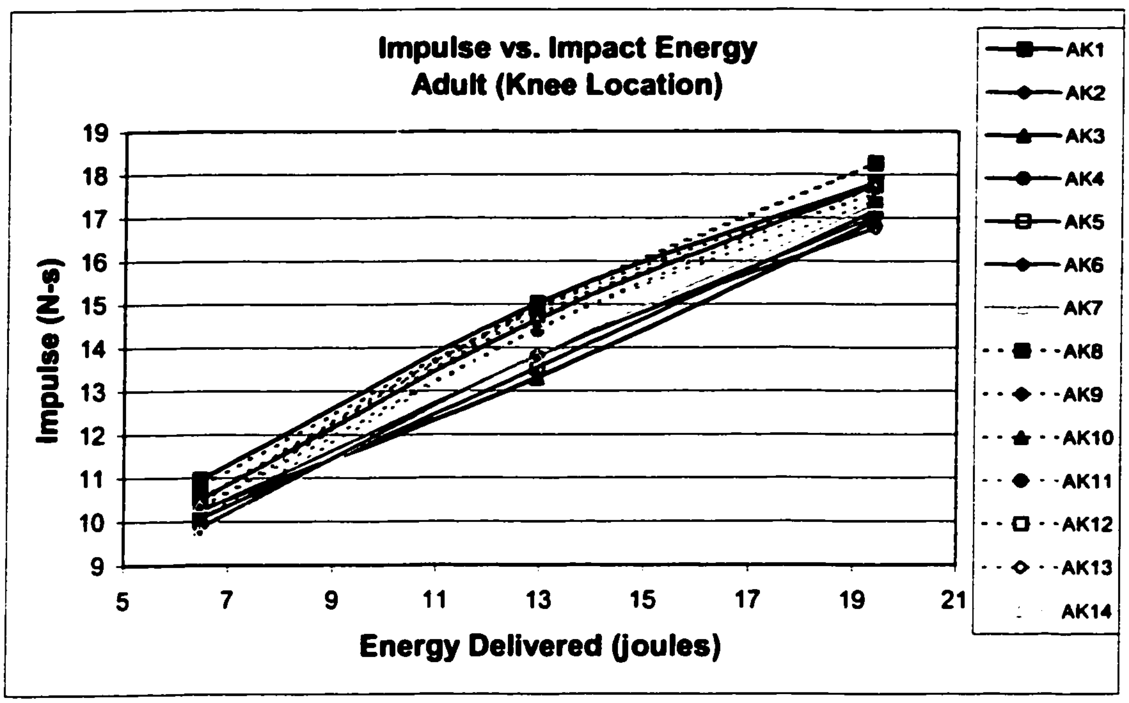
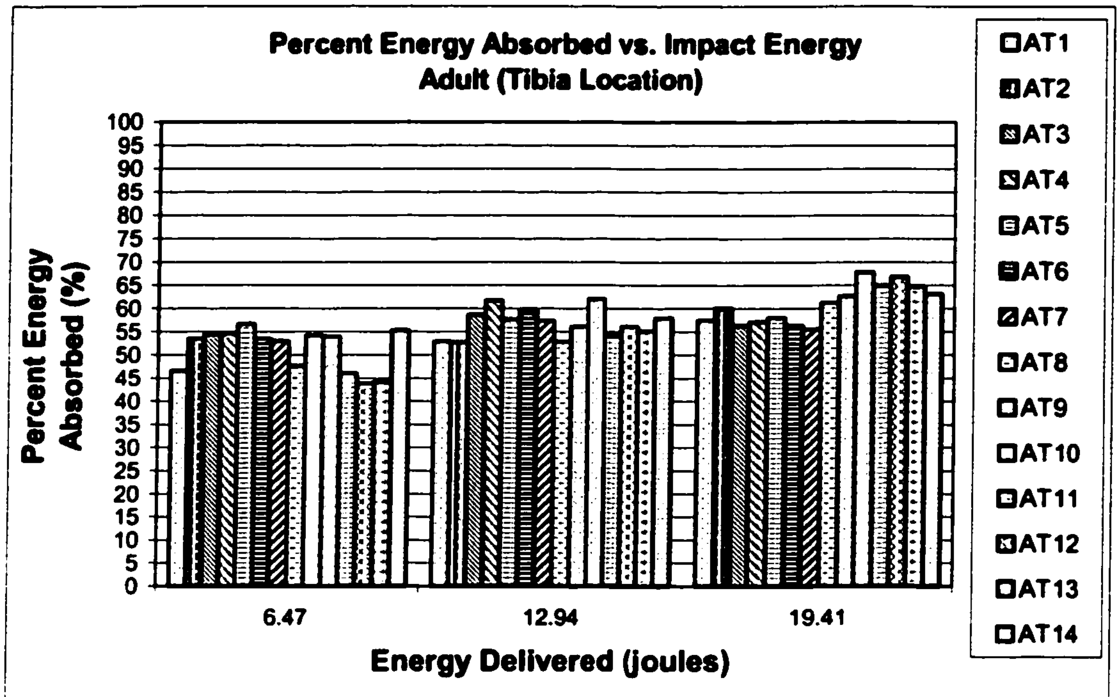
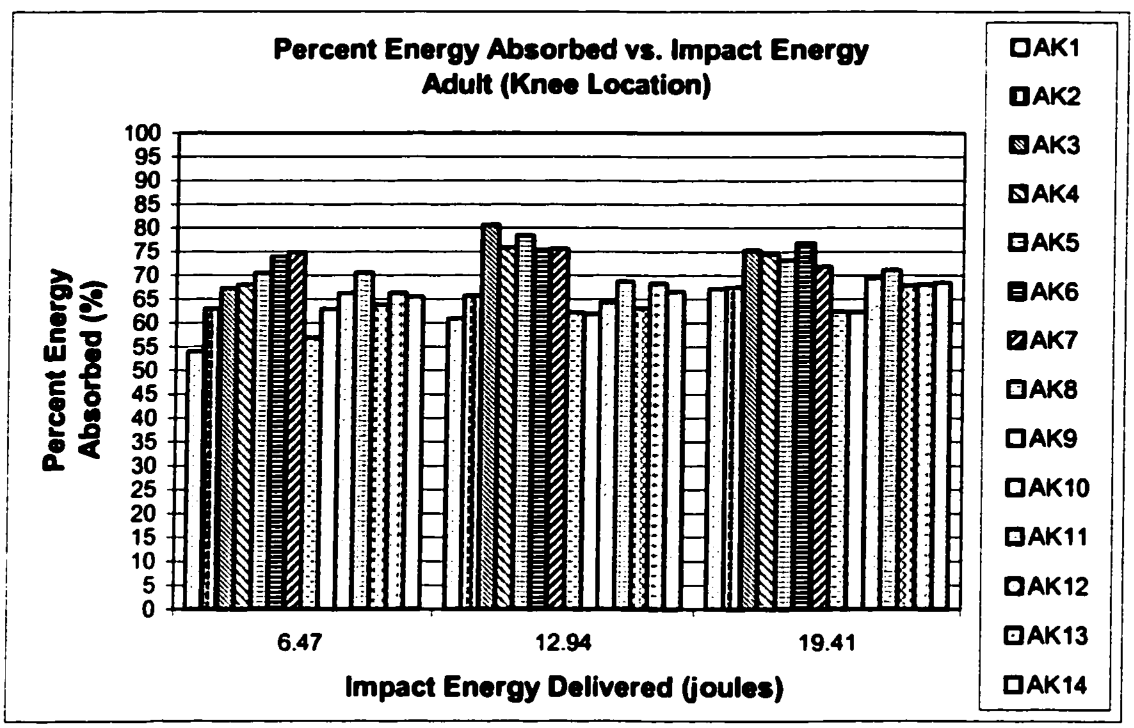


Figure 15. Mean Percent Energy Absorption Values for All Adult Shin Guards, at All Three Impact Energy Levels (Tibia and Knee Locations).





Three sets of five ANOVAs were conducted at the knee location. The first set of five ANOVAs (labeled AK-ANOVA1) consisted of an ANOVA for each of the five dependent variables (F_p, T_p, LR, I and EA) for shin guards that were accepted for all three impact energy level conditions (LOW, MED, HIGH). The adult shin guards included in the five AK-ANOVA1 analyses were AK3, AK4, AK5, and AK6. The results of the five AK-ANOVA1 analyses revealed significant interaction effects ($p<0.05$) of shin guard x impact energy level for all five dependent variables (Table 10). The graphical representation of the interaction effects for the five AK-ANOVA1 analyses, are displayed in Appendix P. Unlike the tibia location, there were shin guards that were accepted for two impact conditions (LOW and MED). Therefore, the second set of five ANOVAs (labeled as AK-ANOVA2) consisted of an ANOVA for each of the five dependent variables for shin guards that were accepted for two impact energy level conditions (LOW and MED). The adult shin guards included in the five AK-ANOVA2 analyses were AK1, AK2, AK3, AK4, AK5, AK6, AK7, AK8, AK12, and AK14. The results of the five AK-ANOVA2 analyses revealed significant interaction effects ($p<0.05$) of shin guard x impact energy level for all five dependent variables (Table 11). The graphical representation of the interaction effects for the five AK-ANOVA2 analyses, are displayed in Appendix Q. The third set of five ANOVAs (labeled AK-ANOVA 3) consisted of an ANOVA for each of the five dependent variables for shin guards that were only accepted at one impact condition (LOW). The adult shin guards included in the five AK-ANOVA3 analyses were AK1, AK2, AK3, AK4, AK5, AK6, AK7, AK8, AK9, AK10, AK12, AK13 and AK14. The results of the five AK-ANOVA3 analyses revealed significant main effects (p<0.05) of shin guard for all five dependent variables (Table 12). The graphical representation of the interaction effects for the five AK-ANOVA3 analyses, are displayed in Appendix R. In addition, the mean values (for each block of 12 drops) for all five dependent variables for all conditions delivered to the knee location are also displayed graphically in Figures 11, 12, 13, 14 and 15.

The results of the *post hoc* comparisons at the knee location are listed in Appendices U, V and W. The results indicated that the analyses including all three impact energy levels (AK-ANOVA1) revealed significant interaction effects of shin guard and impact energy level for all five of the dependent variables (Table 10). *Post Hoc* comparisons in Appendix U revealed that there were several significant comparisons resulting in the statistically significant interaction effects for each of the dependent variables. Upon further investigation of the *post hoc* comparisons, it appeared that the F_p, T_p, LR and I dependent variables were the most effective at identifying significant differences between the shin guards at one particular level.

The results indicated that the analyses including two impact energy levels (AK-ANOVA2) revealed significant interaction effects of shin guard and impact energy level for all five of the dependent variables (Table 11). *Post Hoc* comparisons in Appendix V revealed that there were several significant comparisons resulting in the statistically significant interaction effects for each of the dependent variables. Upon further investigation of the *post hoc* comparisons, it appeared that the F_p, I, and EA dependent variables were the most effective at identifying significant differences between the shin guards at one particular level.

The results indicated that the analyses including only the low impact energy level (AK-ANOVA3) revealed significant main effects of shin guard for all five of the dependent variables (Table 12). *Post Hoc* comparisons in Appendix W revealed that there were several significant comparisons resulting in the statistically significant main effects of shin guard for each of the dependent variables. Upon further investigation of the post hoc comparisons, it appeared that the F_p, I, and EA dependent variables were the most effective at identifying significant differences between the shin guards.

Table 10. Analyses of Variance for Adult Shin Guards Accepted for All Three Impact Energy Levels at the Knee Location (AK-ANOVA1).

Peak Force

Summary of all Effects; design: (ak-anova1.sta)
1-GUARD, 2-PEAK

	df Effect	*MS* Effect	*df* Error	*MS* Error	*F*	*p-level*
1	3	48096.43	44	682.4818	70.47285	7.73E-17*
2	2	4326434	88	152.2876	28409.62	0*
1 x 2	6	13798.9	88	152.2876	90.61079	0*

Time to Peak

Summary of all Effects; design: (ak-anova1.sta)
1-GUARD, 2-TIME

	df Effect	*MS* Effect	*df* Error	*MS* Error	*F*	*p-level*
1		15.73789	44	0.077717	202.5031	9.25E-26*
2	2	0.588545	88	0.069884	8.421746	4.50E-04*
1 x 2	6	5.33864	88	0.069884	76.39294	0*

Loading Rate

Summary of all Effects; design: (ak-anova1.sta)
1-GUARD, 2-LDRT

	df Effect	*MS* Effect	*df* Error	*MS* Error	*F*	*p-level*
1	3	8.85E+09	44	18559608	476.6037	0*
2	2	4.55E+10	88	18607418	2444.248	0*
1 x 2	6	2.23E+09	88	18607418	120.1003	0*

Impulse

Summary of all Effects; design: (ak-anova1.sta)
1-GUARD, 2-IMPULSE

	df Effect	*MS* Effect	*df* Error	*MS* Error	*F*	*p-level*
1	3	0.297664	44	0.008181	36.38318	5.55E-12*
2	2	566.0696	88	0.009252	61186.37	0*
1 x 2	6	0.570355	88	0.009252	61.64954	2.08E-29*

Energy Absorbed

Summary of all Effects; design: (ak-anova1.sta)
1-GUARD, 2-EABSORB

	df Effect	*MS* Effect	*df* Error	*MS* Error	*F*	*p-level*
1	3	0.577354	44	0.016595	34.79173	1.11E-11*
2	2	1210.003	88	0.016577	72992.88	0*
1 x 2	6	1.050999	88	0.016577	63.40105	7.74E-30*

*** Statistically Significant**

Table 11. Analyses of Variance for Adult Shin Guards Accepted for Two Impact Energy Levels at the Knee Location (AK-ANOVA2).

Peak Force

Summary of all Effects; design: (ak-anova2.sta)
1-GUARD, 2-PEAK

	df Effect	*MS* Effect	*df* Error	*MS* Error	*F*	*p-level*
1	9	347016	110	426.6819	813.2896	0*
2	1	5861429	110	135.3313	43311.69	0*
1 x 2	9	40513.56	110	135.3313	299.3657	0*

Time to Peak

Summary of all Effects; design: (ak-anova2.sta)
1-GUARD, 2-TIME

	df Effect	*MS* Effect	*df* Error	*MS* Error	*F*	*p-level*
1	9	25.01886	110	0.146165	171.1687	0*
2	1	0.122944	110	0.173258	0.709604	0.401403
1 x 2	9	5.825127	110	0.173258	33.62118	1.12E-27*

Loading Rate

Summary of all Effects; design: (ak-anova2.sta)
1-GUARD, 2-LDRT

	df Effect	*MS* Effect	*df* Error	*MS* Error	*F*	*p-level*
1	9	8.58E+09	110	14351884	597.6514	0*
2	1	7.65E+10	110	20579018	3716.307	0*
1 x 2	9	2.07E+09	110	20579018	100.6816	0*

Impulse

Summary of all Effects; design: (ak-anova2.sta)
1-GUARD, 2-IMPULSE

	df Effect	*MS* Effect	*df* Error	*MS* Error	*F*	*p-level*
1	9	5.539421	110	0.007902	701.0441	0*
2	1	906.8566	110	0.007199	125969.2	0*
1 x 2	9	1.020826	110	0.007199	141.8004	0*

Energy Absorbed

Summary of all Effects; design: (ak-anova2.sta)
1-GUARD, 2-EABSORB

	df Effect	*MS* Effect	*df* Error	*MS* Error	*F*	*p-level*
1	9	10.76233	110	0.015953	674.6268	0*
2	1	1416.359	110	0.012254	115580.5	0*
1 x 2	9	2.60186	110	0.012254	212.322	0*

*** Statistically Significant**

Table 12. Analyses of Variance for Adult Shin Guards Accepted for One Impact Energy Level at the Knee Location (AK-ANOVA3).

Peak Force

Summary of all Effects; design: (ak-anova3.sta) 1-GUARD						
	df Effect	*MS* Effect	*df* Error	*MS* Error	*F*	*p-level*
1	12	94168.21	143	103.1453	912.9665	0*

Time to Peak

Summary of all Effects; design: (ak-anova3.sta) 1-GUARD						
	df Effect	*MS* Effect	*df* Error	*MS* Error	*F*	*p-level*
1	12	8.160345	143	0.234473	34.80288	0*

Loading Rate

Summary of all Effects; design: (ak-anova3.sta) 1-GUARD						
	df Effect	*MS* Effect	*df* Error	*MS* Error	*F*	*p-level*
1	12	3.26E+09	143	11826494	275.6616	0*

Impulse

Summary of all Effects; design: (ak-anova3.sta) 1-GUARD						
	df Effect	*MS* Effect	*df* Error	*MS* Error	*F*	*p-level*
1	12	1.280957	143	0.006545	*195.708*	*0**

Energy Absorbed

Summary of all Effects; design: (ak-anova3.sta) 1-GUARD						
	df Effect	*MS* Effect	*df* Error	*MS* Error	*F*	*p-level*
1	12	1.738554	143	0.009053	192.0381	0*

*** Statistically Significant**

Chapter 5

Discussion

The results of the junior and adult experiments are discussed in terms of the relative injury prevention provided to athletes using ice hockey shin guards. The relevance of the results to the current impact testing literature is examined, and the relative injury prevention provided by varying quality shin guards and varying impact locations are assessed. Due to a limited sample size and material damage in the junior experiment, the majority of the discussion is focused on the adult experiment. Limitations to the experimental design are also considered.

Junior Experiment

The impact energies delivered to the junior shin guards were considered sub-maximal in magnitude (3.23J, 4.07J, and 4.88J). The findings of the experiment indicated that most junior shin guards displayed some material damage. As a result, the ability of the material to attenuate impact conditions had deteriorated. A 0.160kg puck would only require approximate velocities between 6.3m/s and 7.8m/s to reach the energy range delivered in the junior experiment. A body mass of 30kg would only require approximate average velocities between 0.46m/s and 0.57m/s and fifty percent of that body mass would still only require approximate average velocities between 0.65m/s and 0.81m/s to reach the energy values delivered in the experiment. A 30kg mass falling 0.25m would result in an approximate impact energy level of 73.26J. In fact, it would only require approximately 1.3kg to 2.0kg to fall 0.25m in order to reach the impact energies delivered in this experiment. It is unlikely that young children would be able to reach the above puck velocities, however, caution would have to be taken if these children were exposed to hockey environments including older and stronger athletes, such as older siblings or parents. The above skating and sliding velocities are so low in magnitude, it would seem that even young children could easily surpass them. In this case, the findings of this experiment would suggest that the shin guard material would sustain damage, and the injury prevention provided by the junior shin guards would be diminished. If 0.25m is an approximation of the distance between the knee of a child and the surface of the ice, even the leg segment mass is likely to approach the impact energy range of this experiment. Even for young children, impacts due to a fall will most likely occur with an increased mass, and again, the findings of this experiment would suggest that the shin guard material would sustain some damage and therefore the injury prevention provided by the junior shin guard would be diminished.

Although none of the junior data underwent statistical analyses to determine any main effects of shin guard, impact energy level or interaction effects of shin guard and impact energy level, Figures 6, 7, 8, 9, and 10 have revealed some interesting findings with respect to mechanical response variations of junior shin guards. It is clear to see that at both locations, the junior shin guards displayed variations in mechanical response due to shin guard and due to impact energy delivered.

Peak Force

It appeared that even in a damaged state, shin guards JRT1 and JRT2 typically transmitted lower F_p values than junior shin guard JRT3 for all impact energy levels at the tibia location (see Figure 6). In addition, shin guards JRT1, JRT2, and JRT3 appeared to transmit lower F_p values at all impact energy levels when compared to the baseline foam. However, shin guards JRT4 and JRT5 transmitted higher F_p values when compared to the baseline foam (except at the high impact energy level). At the knee location, all five shin guards transmitted lower F_p values for all impact energy levels when compared to the baseline foam; however, shin guards JRK1, JRK2, JRK3 and JRK4 transmitted lower F_p values than shin guards JRK5 (see Figure 6).

Time to Peak Force

The relationships between increasing impact energy and T_p values obtained in this experiment were unexpected. At both locations, the data in some shin guards would show a decrease in the T_p from the low to the medium impact energy levels however would then show an increase in the T_p from the medium to the high impact energy levels. In contrast, some T_p values would increase from the low to the medium impact energy levels but would then decrease from the medium to high impact energy levels (see Figure 7). Although these unexpected relationships most likely were the result of material damage, some findings can be extracted from the data. At the tibia location, the low impact energy level revealed that all five shin guards had shorter T_p than the baseline foam, with shin guards JRT1 and JRT2 having the longest T_p values (see Figure 6). The medium and high impact energy levels revealed that shin guards JRT3, JRT4, and JRT5 had shorter T_p values than the baseline foam but shin guards JRT1 and JRT2 T_p values where similar or longer than the baseline foam. At the knee location, the low impact energy level revealed that all five shin guards had shorter T_p values than the baseline foam, with guards JRK2, JRK4 and JRK5 having the longest T_p values (see Figure 7). The medium impact energy level revealed that all five shin guards had longer T_p values than the baseline foam, with shin guards JRK1 and JRK4 having the longest T_p values. At the high impact energy level, shin guards JRK1, JRK3, JRK4, and JRK5 once again had shorter T_p values than the baseline foam, but shin guard JRK2 maintained a longer T_p value than the baseline foam.

Loading Rate

The data revealed that loading rates of junior shin guard materials varied, even in damaged state. At the tibia location, shin guards JRT1, JRT2, and JRT3 displayed lower LR values at all impact energy levels when compared to the baseline foam, whereas shin guards JRT4 and JRT5 displayed similar or higher LR values for the low and medium impact energy levels and lower LR values at the higher impact energy level when compared to the baseline foam (see Figure 8). At the knee location, all five shin guards displayed lower LR values when compared to the baseline foam (see Figure 8). It is, however, important to note that although the LR values for shin guard JRK4 were lower than the baseline foam, the value was much higher than the other four shin guards at the high impact energy level.

Impulse and Energy Absorbed

The momentum delivered at any one impact energy level condition was constant due to the fact that the same drop mass and drop height was used for all shin guards. A shin guard that recorded a higher impulse value was considered to be less effective at attenuating the impact force. Even in a damaged state, the junior shin guards displayed some variations in I values at both locations. At the tibia location, all shin guards displayed higher impulse values than the baseline foam at the low and medium impact energy levels (see Figure 9). It was interesting to note that there was little variation in the I values between the five shin guards for the low and medium impact energy levels. However, the variation in I values between the five shin guards at the high impact condition did start to increase; with shin guards JRT3, JRT4 and JRT5 having similar or lower I values when compared to the baseline foam and shin guards JRT1 and JRT2 having higher I values compared to the baseline foam. Similarly at the knee location, all shin guards displayed higher I values than the baseline foam at the low and medium impact energy levels (see Figure 9). At the high impact energy level, shin guard JRK1, JRK2, JRK4, and JRK5 displayed I values slightly higher than the baseline foam, whereas shin guard JRK3 displayed a lower I value when compare to the baseline value. It is also important to note that shin guard JRK3 displayed lower I values that the other four shin guards at all impact energy levels.

In order for a material to reduce the amount of impulse transmitted through it, some energy absorption must take place. Due to the fact that the energy absorption values were derived from the impulse value using the principle of linear impulse and momentum, it can be expected that shin guards that displayed higher I values would also display lower EA values when compared to the baseline foam. This expectation was confirmed for the tibia location as well as the knee location (see Figure 10). At the tibia location, all shin guards showed lower EA values than the baseline foam for the low and medium impact energy levels. At the high impact condition, shin guards JRT1, JRT3, and JRT5 showed EA values very similar to the baseline foam, whereas shin guard JRT2 and JRT4 displayed lower EA values than the baseline foam. Similarly at the knee location, all shin guards displayed lower EA values than the baseline foam at the low and medium impact energy levels (see Figure 10). An interesting finding at the high impact energy level revealed that shin guards JRK1, JRK2, JRK4, and JRK5 displayed EA values slightly higher that the baseline foam values even though the I values were higher than the baseline foam values. As expected, shin guard JRK3 displayed an EA value greater than the baseline foam at the high impact energy level.

In order to provide injury prevention to an athlete, shin guard material must have the ability to reduce peak force, prolong the time to peak force, and as a result, decrease the loading rate transmitted to the tissues of the leg. Injury prevention may also be provided to the athlete, if the shin guard material has the ability to absorb energy and therefore reduce the amount of impulse transmitted to the tissues of the leg. The findings of the junior experiment would suggest that the mechanical responses of shin guards JRT1, JRT2, JRT3 at the tibia location and JRK1, JRK2, JRK3, and JRK5 at the knee location provided superior injury prevention to the athlete based on the dependent variables investigated in this experiment.

Overall, even in a damaged state, it can be said that junior shin guards had varying mechanical responses to various impact energy levels. In addition, the mechanical response of one shin guard tended to vary between the tibia and knee locations. In fact, junior shin guards JR1 and JR2 were the same brand and model number and junior shin guards JR4 and JR5 were the same brand and model number. Therefore, even identical shin guards had different mechanical responses to impact energy levels and locations. However, this result may be due to the fact that the impact energies were delivered in a random order. Depending on the order of the delivered conditions, one shin guard may have sustained material damage earlier in the experiment. Data collected after the material damage occurred would be skewed and would therefore result in a different mechanical response of that shin guard. It was slightly alarming, that some junior shin guards displayed less favorable mechanical responses to impact conditions than the baseline foam, particularly since the baseline foam did not have a hard plastic covering like the shin guards did. It appears that under some impact conditions delivered in this experiment, more injury prevention might be provided by a double layer of foam or a material with similar characteristics.

Adult Experiment

The impact energies delivered to the adult shin guards were considered sub-maximal in magnitude (6.47J, 12.9J, and19.4J). The findings of the experiment indicated that selected shin guards displayed some material damage. As a result, the ability of the material to attenuate impact conditions had deteriorated. A 0.160kg puck would only require approximate velocities between 9.2m/s and 15.6m/s to reach the energy range delivered in the adult experiment. A 50th percentile mass (73kg) of men aged 20-29 years (Reid, 1992, p1991), would only require estimated average skating or sliding velocities between 0.42m/s and 0.73m/s to reach the energy values delivered in the experiment. Fifty percent of that body mass (36.5kg) would still only require estimated average velocities between 0.60m/s and 1.0m/s to reach the energy values delivered in the experiment. A 73kg mass falling 0.5m would result in an estimated impact energy level of 358.1J. In fact, it would only require an estimated 1.3kg to 4.0kg to fall 0.5m in order to reach the impact energies delivered in this experiment. Maximal puck velocities have been reported to range between 24.24m/s and 39.38m/s (Sim et al., 1978). These puck velocities can represent estimated impact energies in the magnitude ranging from 47.04J to 124.1J. Maximal skating velocities have been reported between 8.89m/s and 12.12m/s in the forward direction and 6.82m/s and 7.57m/s in the backward direction (Pfoerringer & Smasal, 1987; Sim, 1987). These skating velocities can represent estimated impact energies in the magnitude of 2880J to 5360J for a full body mass impact of 73kg in the forward direction and 1700J to 2090J in the backward direction. Even a 50th percentile leg segment mass of 3.47kg (Plagenhof, Evans & Abdelnour, 1983) traveling at the above skating velocities can represent estimated impact energies in the magnitude of 137J to 255J in the forward direction and 80.7J to 99.4J in the backward direction. Sliding velocities have been reported to reach a maximum of 6.67m/s (Sim et al, 1987). A full body mass impact of 73kg traveling at this velocity can result in an estimated impact energy of 1620J and a leg segment mass of 3.47kg can result in an estimated impact energy of 77.2J. If 0.5m is an approximation of the distance between the knee of an adult and the surface of the ice, a 73kg full body mass vertical fall can result in an estimated impact energy of 358J. Even the leg segment mass of 3.47kg will represent an estimated impact energy of 17.0J. It therefore becomes apparent that the impact energy levels of 6.47J, 12.9J and19.4J delivered in this experiment, are representative of sub-maximal impact conditions that may occur in the sport of ice hockey.

The data obtained in the adult experiment did reveal that selected adult shin guards were capable of attenuating impact forces at selected or all of the impact conditions delivered at either location. However, other adult shin guards did sustain material damage at the knee and tibia locations, even at these sub-maximal impact energy levels. In order to prevent any damage to the leg form and compression force transducer, baseline values were not collected in the adult experiment as they were in the junior experiment. However, the adult shin guards were separated into mid-level and high-level quality groups as specified by each manufacturer. The manufacturers classified adult shin guards A1, A2, A3, A4, A5, A6, and A7 as mid-level quality (represented by solid lines in Figures 11, 12, 13, 14, and 15) and adult shin guards A8, A9, A10, A11, A12, A13, and A14 as high-level quality (represented by dashed lines in Figures 11, 12, 13, 14, and 15). Therefore, the results obtained for the statistical analyses are discussed in terms of a) a comparison of the findings in this experiment with the findings of previous impact testing, b) a comparison of shin guards, and c) a comparison between the two impact locations.

Comparisons to Previous Impact Testing

Although no studies investigating ice hockey shin guards have been published in the scientific literature, results from this investigation can be compared to other areas of material testing. Comparisons to areas such as the impact testing of soccer shin guards, hip padding and athletic footwear can help put the results of this experiment into perspective.

Francisco et al. (2000) investigated the mechanical response of soccer shin guards to typical impact conditions experienced in the sport of soccer. Soccer shin guards were tested using a synthetic tibia model. Prior to shin guard testing, the reliability of the tibia model was evaluated based on the mechanical response of cadaver tibias. Using energy levels of 3.02J to 13.1J, the cadaver tibias were impacted to the point of failure. The average peak force required fracture the cadaver tibias was determined to be 2927 $\pm$ 403N. Using a slightly higher impact energy range of 6.07J to 15.3J, peak force values transmitted through the shin guards were recorded. The authors observed peak force values ranging between 1336N to 2232N for the 6.07J to 15.3J range. Although the maximum energy level used in the experiment by Francisco et al. (2000) was higher than the maximum impact energy level in the current investigation, the remaining impact energy levels (6.07J to 13.1J) were similar.

The peak force values transmitted through the average soccer shin guard (averaged Fp for all shin guards used in experiment) ranged from 1111N to 1723N. In comparison, the peak for values recorded with the average ice hockey shin guard ranged from 558.6N to 1852N at the tibia location and 544.6N to 1342N at the knee location (see Appendices L & M). Although the proportion of mass and velocity used to obtain the impact energy levels were lightly different, similar peak force values were recorded at the tibia location. However, it appears that the ice hockey shin guards attenuated more peak force at the lower impact energy level and less at the high impact energy level when compared to the soccer shin guards. The knee location of the ice hockey shin guards on the other hand, appeared to attenuate more peak force throughout the impact energy range. Therefore, similar to the conclusions drawn by Francisco et al. (2000), ice hockey shin guards alone appeared to attenuate peak forces below the threshold value of 2927 $\pm$ 403N required to fracture the tibia. Although ice hockey shin guard material in the current investigation did sustain damage, they still provided injury prevention against tibia fractures to the athlete.

In both the current investigation and the research done by Francisco et al. (2000), force attenuation provided by soft tissues of the leg was neglected. Hip padding research has shown that, depending on the thickness, soft tissue at the hip accounted for 6% to 58% of the energy absorption during impact

(Robinovitch, McMahon and Hayes, 1995). In addition, the authors observed an average of 13 $\pm$ 15% reduction in peak force. Therefore, although the peak force values recorded in the current investigation were below fracture threshold values, it is likely the peak forces recorded would be even lower in magnitude through soft tissue.

The amount of force transmitted through a shin guard can be used to evaluate a shin guard's ability to protect an athlete against injury. Ideally, a shin guard should be able to reduce the amount of force applied to the soft and osseous tissues of the knee and leg. The findings of the adult experiment support the assumption that there is a relationship between impact forces and the properties of the material (Cavanagh & Lafortune, 1980: Nigg, 1987; Rodano, 1983). Shin guards that displayed higher loading rates at a given location also display corresponding higher peak force values. If the loading rate can be an indirect measure of hardness (McCaw, 2000), the results are in agreement with the finding that peak impact forces are reduced for softer, thicker material in comparison to harder material (Lees & McCullagh, 1984). Therefore, more compliant shin guards with the ability to reduce the magnitude of peak forces can provide superior injury prevention to the athlete.

The time required to attain peak force is often measured in conjunction with peak force and loading rate values. The time over which a force is applied is dependent upon the characteristics of the material that force is applied to. It remains inconclusive if the time to peak force results revealed in the adult experiment, resembled findings that softer material can delay the time to peak of impact forces and as a result, reduced the loading rate (Lees & McCullagh, 1984). More compliant material that was characterized by lower loading rates did not clearly indicate a prolonged time to peak force in the current investigation.

The impulse and energy absorption results of the junior and adult experiments did appear to support the findings of McCullagh & Graham (1985). Adult shin guard materials displayed an ability to dissipate or absorb energy, even in a damaged state. Similar to the findings of previous research, different materials absorbed different amounts of energy for a particular load and the amount of energy absorbed in shin guard material decreased as the loading rate increased for the same maximal load (McCullagh & Graham, 1985). In addition, materials that attenuated peak forces to a similar degree displayed different amounts of energy absorption (Clark & Frederick, 1982). Therefore more compliant shin guard material, characterized by lower loading rates, did absorb more energy than harder shin guard material. However, different compliant shin guard material did reveal variations in the amount of energy that was absorbed. Therefore more compliant shin guard material can offer superior injury prevention to the athlete, however that degree of injury prevention still varies between different shin guards.

Comparison of Shin Guards

Several interesting findings emerged from the experiment with respect to the two qualities of shin guards specified by the manufacturers. It is important to note that the level of quality specified by each manufacturer was not specific to any injury prevention qualities that shin guard might have. The quality was specified by the manufacturer, but any reasoning for this classification was unknown to the experimenter. Therefore, the quality level might not be associated with an injury prevention quality. Any detailed comparison between the two qualities of shin guards may therefore, be confounded by the reasoning behind the classification. Recall that all high-level quality shin guards were excluded from the statistical analyses that included all three impact energy levels. Adult shin guards A3, A4, A5 and A6 were the same brand and model number but were different sizes and adult shin guard A7 was the same brand as A3, A4, A5, and A6 but was a different model number. It is particularly interesting that only these mid-level quality shin guards were included in the analyses for all three impact energy levels. Analyses that included one or two of the impact energy levels did however accept shin guards of both mid-level and high-level quality. Another interesting finding is that, although adult shin guards A1 and A2 were the same brand and model and adult shin guards A12 and A13 were the same brand and model number, these pairs of shin guards were not necessarily included/excluded as a pair from any of the analyses. These results would suggest that identical shin guards did not necessarily have the same mechanical response to the same impact conditions delivered. However, this result may be due to the fact that the impact energies were delivered in a random order. Depending on the order of the delivered conditions, one shin guard may have sustained material damage earlier in the experiment. Data collected after the material damage occurred would be skewed and would therefore result in a different mechanical response for that shin guard.

Although the statistical analyses have revealed main effects of shin guard and interaction effects of shin guard and impact energy level, additional trends can be extracted from the comparison of all shin guard data, for all three impact energy levels at both locations. The mean values (for a lock of 12 drops) for all five dependent variables of all adult shin guards are represented in Figures 11, 12, 13, 14, and 15.

Peak Force

The mean F_p values for all shin guards at every condition for the tibia location are represented in Figure 11. Although not all conditions displayed in Figure 11 were included in the statistical analyses, the mid-level and high-level quality shin guards tended to have similar mechanical responses when measuring the F_p dependent variable. At the low impact energy level, there seemed to be little difference between the mid-level and high-level quality shin guards. However, the variation in mechanical response between two quality groups started to increase at the medium impact energy level and increased to a larger extent at the high impact energy level with the high-level quality shin guards performing less favorably than the mid-level quality shin guards. It is important to note that the variation in mechanical response within the mid-level quality group did remain smaller than the variation in mechanical response for the high-level quality group. The mean F_p values for all shin guards at every condition for the knee location are also represented in Figure 11. Unlike the tibia location, the variation in mechanical response between the two quality groups and within each of the quality groups did not change as considerably. Therefore neither group had a more favorable mechanical response over the other at any of the impact energy level delivered to the knee location.

Time to Peak Force

The relationships between increasing impact energy and T_p values obtained in the adult experiment were unexpected. At the tibia location, the data for some shin guards showed an increase in the T_p values from the low to the medium impact energy levels, however would then show a decrease in the T_p values from the medium to the high impact energy levels. In contrast, some shin guard data would show a decrease from the low to medium impact energy levels and then an increase from the medium to the high impact energy levels (see Figure 12). Although these unexpected relationships were most likely the result of material damage, some findings can be extracted from the data. The mean T_p values for all shin guards at every condition for the tibia location are represented in Figure 12. It becomes apparent that identifying variation in mechanical responses between the mid-quality and high-level quality groups and within any one group is difficult; especially considering the difference in T_p values are very small in magnitude. The mean T_p values for all shin guards at every condition for the knee location are also represented in Figure 12. Similarly to the tibia location, identifying variation in mechanical responses between the mid-quality and high-level quality groups and within any one group is difficult; especially considering the difference in T_p values are very small in magnitude.

Loading Rate

The mean LR values for all shin guards at every condition for the tibia location are represented in Figure 13. Although not all conditions displayed in Figure 13 were included in the statistical analyses, the mid-level and high-level quality shin guards tended to have similar within group mechanical responses when measuring the LR dependent variable. At the low impact energy level, there seemed to be little difference between the mid-level and high-level quality shin guards. However, the variation in mechanical response between two groups started to increase at the medium impact energy level and increased to a larger extent at the high impact energy level with the high-level quality shin guards performing less favorably than the mid-level quality shin guards. The mean LR values for all shin guards at every condition for the knee location are also represented in Figure 13. Unlike the tibia location, the variation in mechanical response between the two quality groups and within each of the quality groups did not change as drastically across the impact energy levels. Therefore, neither group had a more favorable mechanical response over the other at any of the impact energy levels delivered at the knee location.

Impulse and Energy Absorbed

The momentum delivered at any one impact energy level condition was constant due to the fact that the same drop mass and drop height was used for all shin guards. A shin guard that recorded a higher impulse value was considered to be less effective at attenuating the impact force. The mean I values for all shin guards at every condition for the tibia location are represented in Figure 14. At the tibia location, very little variation in the mechanical responses appeared between the mid-level and high-level quality shin guards. In fact, little variation in the mechanical response appeared within either quality group. The mean I values for all shin guards at every condition for the knee location are also represented in Figure 14. There appeared to be a similar variation between the mid-level and high-level quality shin guards at all three impact energy levels. However, the mid-level quality appeared to have a more favorable mechanical response at all three impact energy levels.

In order for a material to reduce the amount of impulse transmitted through it, some energy absorption must have taken place. Due to the fact that the energy absorption values were derived from the impulse value using the principle of linear impulse and momentum, it was expected that shin guards that displayed higher I values would also display corresponding lower EA values. At the tibia location, due to the relatively small variation in I between the two quality groups, neither group clearly absorbed more energy than the other at any of the impact energy levels (see Figure 15). Therefore the small variation in the mechanical responses between the mid-level and high-level quality shin guards at the tibia location was also displayed in the EA values. EA values at the knee location did however reveal higher EA values corresponding to the lower I values displayed at the knee location (see Figure 15).

Generally, both the mid-level quality and high-level quality shin guards tended to respond similarly as groups, to the impact conditions delivered in this experiment. However, there did appear to be more variability within the high-level quality group when compared to the mid-level quality group. The two quality groups did tend to have similar mechanical responses at the first two impact energy levels, however at the high impact energy level, the mid-quality shin guards did appear to provide superior injury prevention to the athlete. Overall, the findings of this investigation would suggest that the mid-level quality shin guards were superior at providing injury prevention to the athlete based on the within group variability and the dependent variables measured.

Impact Location Comparisons

Although the statistical analyses for each location were conducted independently, it is important to note that the mechanical response of adult shin guards varied between the tibia and knee location. Upon further investigation of the five dependent variables, it appeared that the knee location of adult shin guards had more favorable mechanical responses to the impact conditions delivered in the experiment. The F_p values for all shin guards (even shin guards that had sustained material damage) tended to be lower in magnitude at the knee location. In addition, the F_p values recorded at the high impact energy level for the knee location were similar to the F_p values recorded at the medium impact energy level at the tibia location (see Figure 11). Although the same trends do not appear to be present in the T_p values initially, further inspection revealed that the T_p values for those of the shin guards that did not sustain material damage tended to be higher at the knee location as opposed to the tibia location (see Figure 12). The LR values for all shin guards (even shin guards that had sustained material damage) tended to be lower in magnitude at the knee location as opposed to the LR rates at the tibia location (see Figure 13). In addition, the LR values recorded at the high impact energy level for the knee location were similar to the LR values recorded at the medium impact energy level at the tibia location (see Figure 13). Although the I values recorded at the knee location were very similar to I values recorded at the tibia location, the values at the tibia did appear to be slightly larger in magnitude at each of the impact energy levels (see Figure 14). As a result, the EA values at the knee location did tend to be larger than the knee location, even for those shin guards that displayed material damage (see Figure 15).

The findings of this investigation would suggest that knee location of adult shin guards provided more injury prevention to the athlete when compared to the tibia location. This finding is of particular interest because it is likely that the knee is subjected to larger impact energies (due to body mass impacts) in real life situations. The tibia location is less likely to encounter larger impact energies due to the restriction of the hockey skate. It would be very difficult to have the tibia location contact a surface when sliding into the boards or falling to the ice. The knee location however, could very easily contact a surface when colliding with the boards or the ice. It therefore becomes important to ensure the knee location of shin guards provide adequate injury prevention against the larger impact energies.

Limitations

The results obtained in this investigation have revealed some limitations associated with the experimental design of the experiments. These limitations may influence the conclusions of this investigation, and therefore must be taken into consideration. Prior to the experiment, there was an assumption that sub-maximal impacts delivered in the experiment would not damage or alter the mechanical response of the shin guard material to impact conditions. It was assumed that ice hockey shin guards were designed to protect the knee and leg against several sub-maximal impacts during the time of its usage. Unfortunately, even at the sub-maximal impact energies delivered in the experiments, several shin guards appeared to have sustained damage. As a result, the data from shin guards displaying damage were excluded from statistical analyses. This presence of material damage did become a significant limitation to the investigation. Although differences that appeared in the mechanical response of varying quality shin guards (even in a damaged state) were very interesting; a complete evaluation of these differences is limited due to the fact that some material sustained damage. It would intuitively be expected that undamaged shin guards would have a more favorable mechanical response than damaged shin guards, however, it is unclear if the differences between shin guards observed in this experiment would have appeared if some shin guard material had not sustained damaged. Therefore, if none of the shin guards tested in the junior and adult experiments had sustained damage, the differences existing between the varying quality shin guards might not have appeared or might have followed a different trend. It is also important to note that the extent to which shin guard material had been damaged was unknown. Some shin guard material may have been defective, fatigued, slightly damaged or even damaged to the point of failure. Shin guards donated for the investigation were believed to be unused and free from defects. However, it is possible that defects may have existed in the material. A full understanding of the degree of material fatigue, damage or complete failure sustained by the shin guards is beyond the scope of this experiment. Shin guard data that showed any degree of damage, characterized by t-test comparisons and coefficients of variation criteria, were simply excluded from statistical analyses.

Another limitation revealed in this investigation, was the influence of the impacting entity. The impacts in the junior and adult experiments were delivered with a sphere shaped drop mass. The resulting circular impacting area had an approximate diameter of 1.0 to 1.5 cm. Therefore, the energies delivered were concentrated to a very small area of the shin guard material. The impacting areas encountered in the sport of ice hockey are likely to be larger and consist of a flatter surface. In addition, the drop mass was made of steel, and therefore consisted of a very unforgiving material. With the exception of the goal post, all surfaces in a real hockey environment are likely to be more forgiving. Very little of the impact energy was absorbed by the impacting entity and as a result, was transferred to the shin guard material. In addition, 45 impacts were delivered to that same concentrated area for each location of each shin guard. Although a shin guard is designed to sustain many impacts during the course of its usage, it is very unlikely that all impacts would be concentrated in such a small area. It is also very unlikely that a shin guard would sustain 45 impacts to the exact same location.

Design characteristics of the individual shin guards were not investigated and may have also been another limitation to the experiment. Measures such as mass, length, and thickness may be important factors when evaluating the mechanical response to impact conditions of varying quality shin guards. Variations in design characteristics may therefore have contributed to the large variation in mechanical responses between the individual shin guards.

Chapter 6

Conclusions

The purpose of this experiment was to test the mechanical response of varying quality ice hockey shin guards under appropriate impact conditions. The impact conditions delivered in both the junior and adult experiments were intended to simulate typical sub-maximal impact situations encountered by shin guards in the sport of ice hockey. Due to the large variation in shin guard quality, junior shin guards were analyzed independently from adult shin guards.

The results of the junior experiment revealed that many shin guards included in the experiment sustained some degree of material damage. However, even in a damaged state, variations in mechanical response to impact conditions did exist between the shin guards. Not only did junior shin guards vary from one another in their mechanical responses to the impact conditions, variations in mechanical responses also existed between the tibia and knee locations of any one shin guard. In addition, even shin guards of the same brand and model number varied in their mechanical responses to the impact conditions delivered in this experiment. Alarmingly, for some impact conditions, it appeared that a double layer of foam (without a hard plastic covering) attenuated more force than some of the junior shin guards. In light of the limitations of the experiment, the real life performance of the junior shin guards used in these investigations remains unclear. Further investigation is required to determine if the junior shin guards used in this experiment would produce the same results if exposed to similar impact energy levels in a real life environment. However, even with or without material damage, it is likely that there will be variations in mechanical response to impact conditions among different shin guards. It can be concluded from this investigation, that some junior shin guards had more favorable mechanical responses to the impact conditions delivered in the experiment, and could therefore provide superior injury prevention to young athletes.

The results of the adult experiment provided further insight into the mechanical response of varying quality adult shin guards. Results revealed some shin guards used in the experiment sustained some degree of material damage. Upon further investigation of the quality of shin guards used in the experiment, only shin guards that were classified mid-level by the manufacturers were included in statistical analyses for all three impact energy levels delivered. Statistical analyses that included one or two of the impact energy levels delivered in the experiment did however include more of the high-level quality shin guards. Significant interaction effects ($p<0.05$) of shin guard and impact energy level were revealed for all ANOVAs performed that included two or three impact energy levels (AT-ANOVA1, AK-ANOVA1, AND AK-ANOVA2). For the ANOVAs performed including only one impact energy level, significant main effects ($p<0.05$) of shin guard were revealed (AT-ANOVA2 AND AK-ANOVA3). Of the five dependent variables investigated for each set of ANOVAs (F_p, T_p, LR, I and EA), it appeared that F_p and LR were more effective at identifying significant differences between shin guards. Therefore variation in mechanical response to impact conditions varied among the shin guards included in the statistical analyses and those that were excluded due to material damage. Similarly to the junior experiment, not only did adult shin guards vary from one another in their mechanical responses to the impact conditions, variations in mechanical responses also existed between the tibia and knee locations of any one shin guard. In addition, even shin guards of the same brand and model number varied in their mechanical responses to the impact conditions delivered in this experiment.

The results of this investigation did seem to be in agreement with findings from previous material impact testing. Ice hockey shin guards (even in a damaged state) did provide injury prevention against tibia fractures to athletes. Softer or more compliant shin guards, as characterized by lower loading rate values, did tend to reduce peak force, and increase time to peak force values. As a result, more compliant shin guards transmitted less of an impulse and therefore absorbed more energy in the process. These finding suggest that more compliant shin guards can offer a superior degree of injury prevention for athletes.

In light of the limitations of the experiment, the real life performance of the adult shin guards used in this investigations remains unclear. Further investigation is required to determine if the adult shin guards used in this experiment would produce the same results if exposed to similar impact energy levels in a real life environment. However, even with or without material damage, it is likely that there will be variations in mechanical response to impact conditions among different shin guards. It can however be concluded from this investigation that mid-level quality shin guards did have more favorable mechanical responses to the impact conditions delivered in the experiment. Although all adult shin guards appeared to provide some degree of injury prevention to the athlete, the shin guards that did not sustain material damage appeared to provide superior injury prevention.

Implications

In terms of practical applications, all shin guards used in this investigation did provide some degree of injury prevention when compared to no protection at all. Even in a damaged state, the degree of injury prevention provided by each shin guard appeared to vary. In the adult experiment, shin guards classified as mid-quality by the manufacturers appeared to provide superior injury prevention compared to high-level quality shin guards. This finding would suggest that classifications used by ice hockey manufacturers might need to be clarified or even reconsidered. As previously mentioned, the reasoning behind the classification of shin guards was unknown to the experimenter. If the reasoning was based on injury prevention characteristics provided by a shin guard, the findings of this investigation would necessitate a reconsideration of the classification. If the reasoning was based on aesthetics or cost of a shin guard, the classification of mid-level or high-level might be misleading.

Future Directions & Recommendations

In order to gain a better understanding of varying quality ice hockey shin guards, several changes can be made to the present experiment. First and foremost, the impact conditions delivered in any experiment should simulate real life conditions as closely as possible. The impacting area used to deliver the impacts should be more representative of the impacting areas encountered in real hockey conditions. Although an ice hockey shin guard is designed to sustain several impacts during the course of its usage, an independent measures design may help to alleviate the problematic issue of material damage. In the current investigation, a given shin guard was subjected to repeated impacts at varying impact energy levels. Three separate samples of identical shin guards may have helped to eliminate some of the problems encountered with material fatigue or damage. In addition, it may not be necessary to deliver the same amount of individual impacts at every condition. The variation appeared to be very small for a block of 15 drops, for a condition where the material did not appear to sustain damage. Reducing the number of drops would therefore not skew any result obtained and might in fact be beneficial in preserving the shin guard material. Incorporating design characteristics may also be beneficial in identifying the variations between shin guards.

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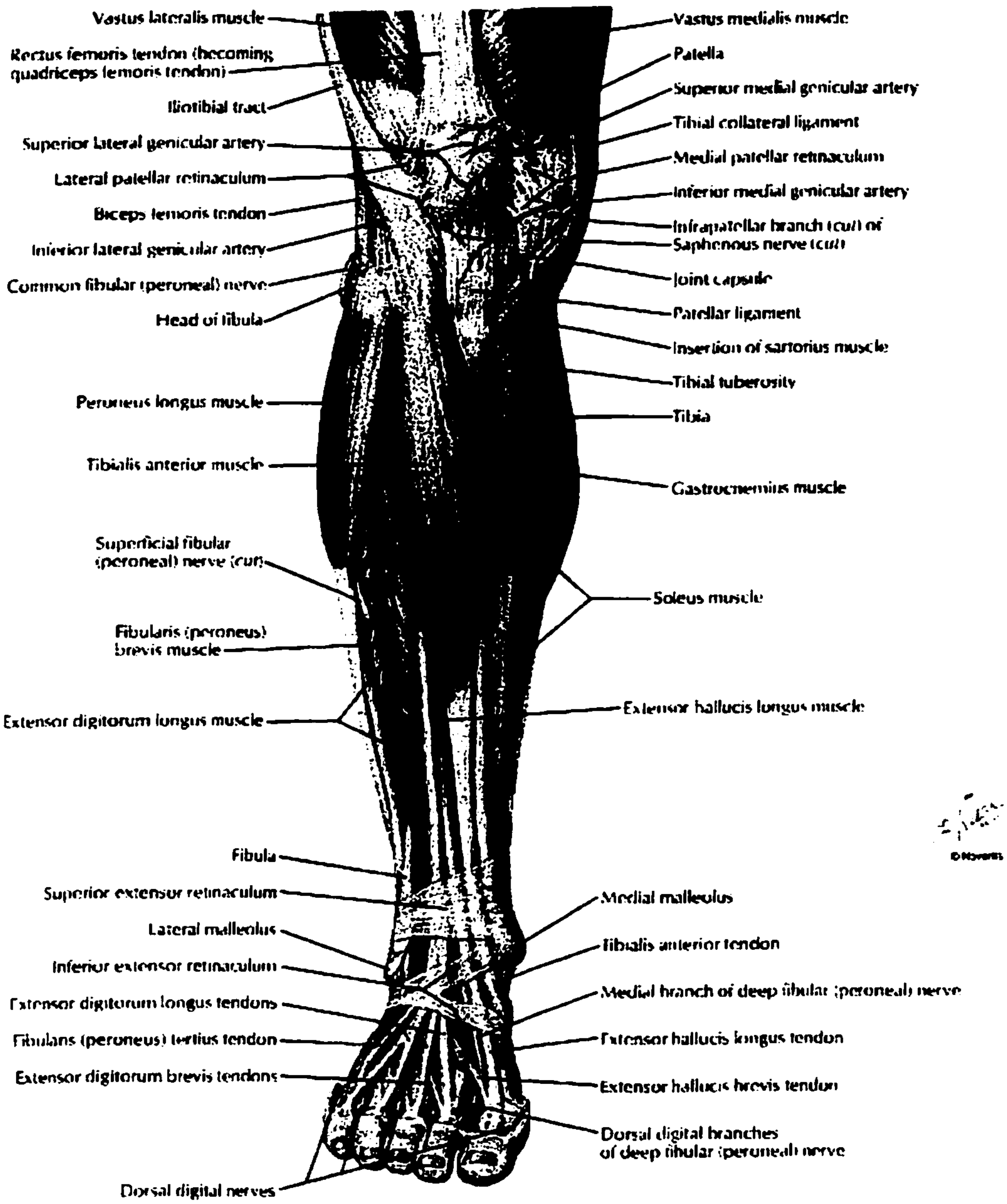
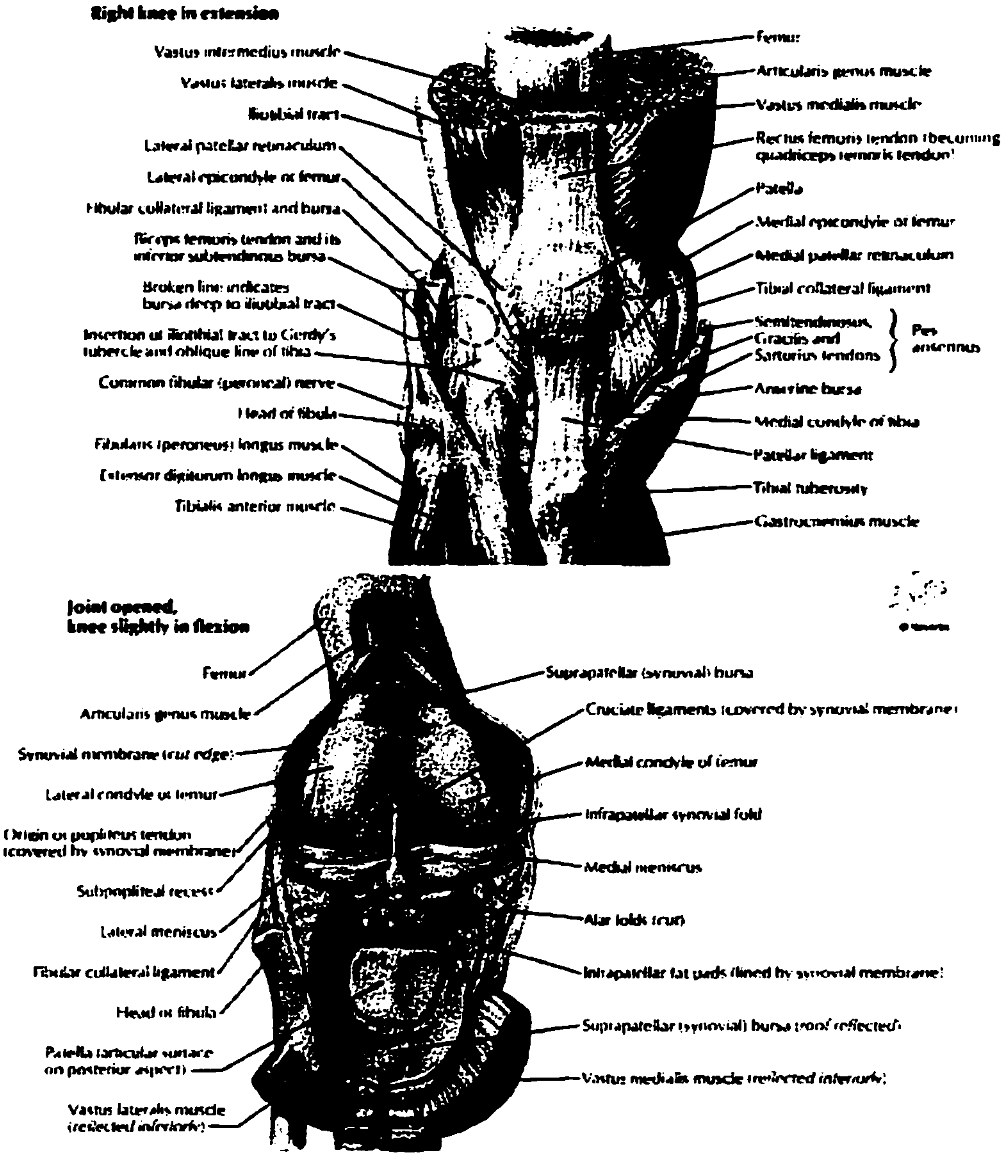
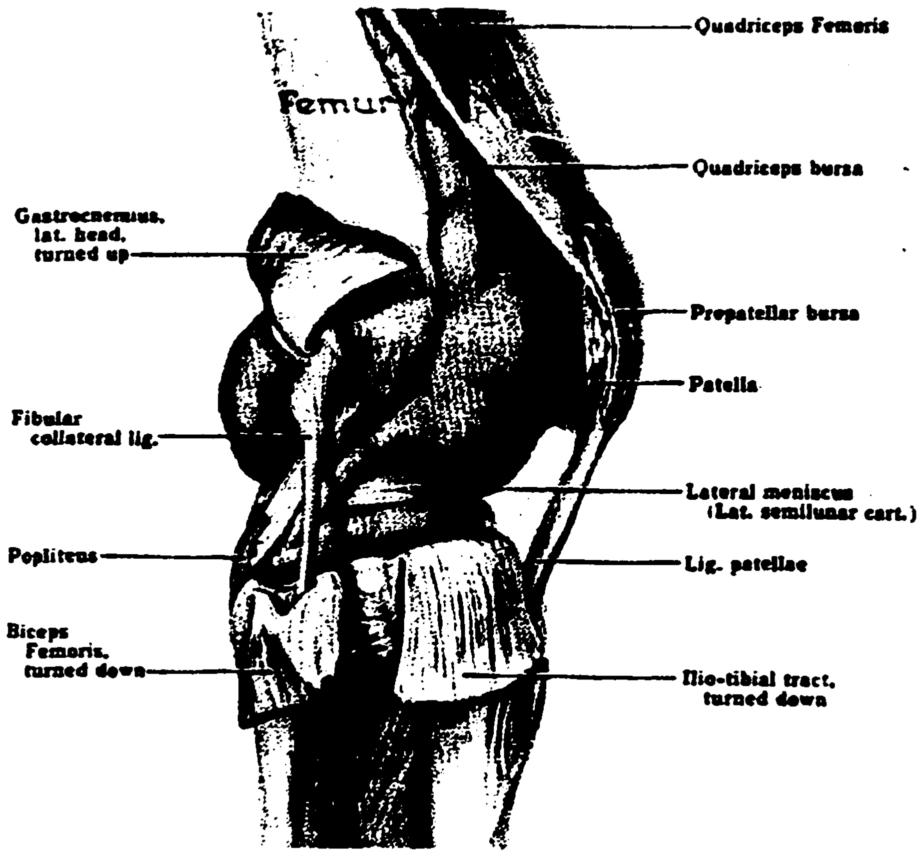
Appendix A. Anatomy of the Leg, Anterior View (Netter, 1997, plate 484).



Appendix B. Anatomy of the Leg, Anterior View (Netter, 1997, plate 473).



Appendix C. Anatomy of the Knee, Lateral View (Reid, 1992, p. 418)



Appendix D. Sample Letter Sent to Hockey Companies

January 28, 2002

Product Manager,

Subject: Shin guard testing

My name is Kim Fournier and I am a graduate student at the University of Windsor. I am currently working towards my master's degree in Human Kinetics, with a specialization in the field of Applied Sports Biomechanics. I am presently working on my thesis with Dr. Wayne Marino and plan to conduct an experiment testing the effectiveness of ice hockey shin guards.

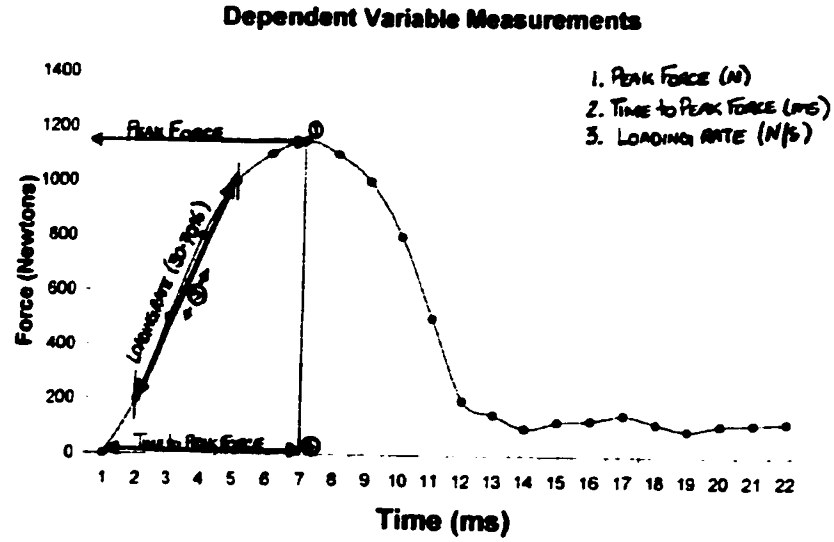
The purpose of my experiment will be to test the effectiveness of design characteristics in various age and skill level, ice hockey shin guards. Force attenuating properties of ice hockey shin guards such as force transmission and force dispersion will be evaluated. In order to perform such an experiment, ice hockey shin guards from various manufacturers, that are of various age and skill levels are required. It is at this point, that I would like to request some assistance from your company in my research. More specifically, I would like to know if you would consider donating a pair of youth and adult ice hockey shin guards of any skill level to my thesis experiment. They do not have to be from the current season and imperfections in design (such as color or lettering) are acceptable. I would also be pleased to return the product to your company once the experiment is completed. Your assistance would be greatly appreciated and would be instrumental in helping me complete my thesis work at the University of Windsor.

It is important to note that the purpose of the experiment is *not* to evaluate one company with respect to another company, but rather, to evaluate differences that might exist between various levels of ice hockey shin guards regardless of the make. I would be pleased to provide Company X with an executive summary of the experiment including the data related to your product. I hope Company X might be willing to contribute to the furthering of academic equipment testing in the sport of ice hockey. I would like to take this opportunity to thank you for your time and consideration. Any comments or concerns you might have with respect to my research are welcome and encouraged. I look forward to you response.

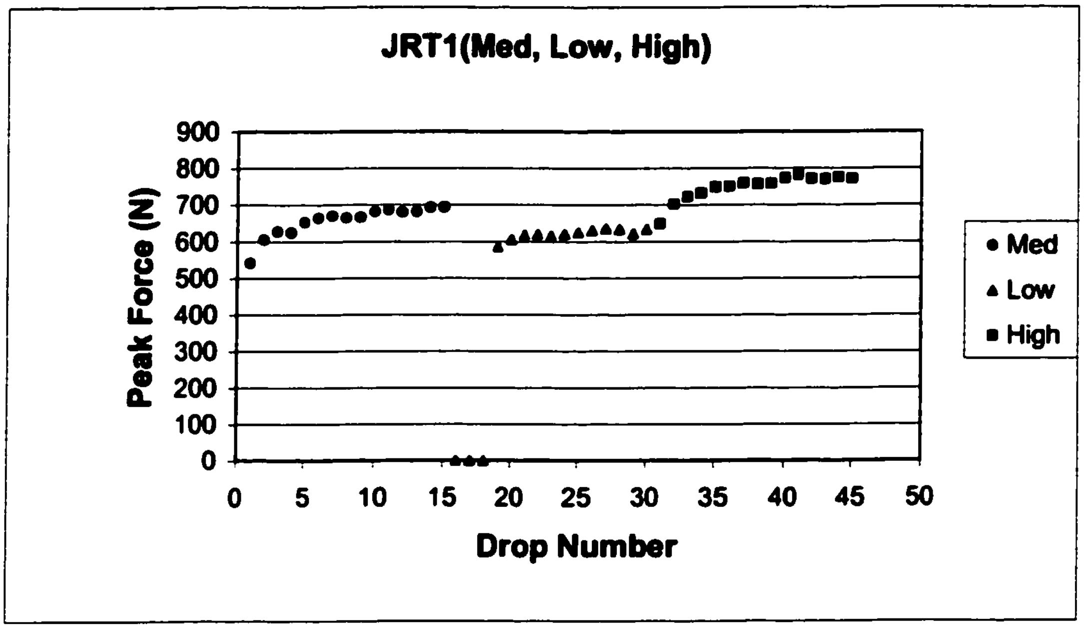
Respectfully,

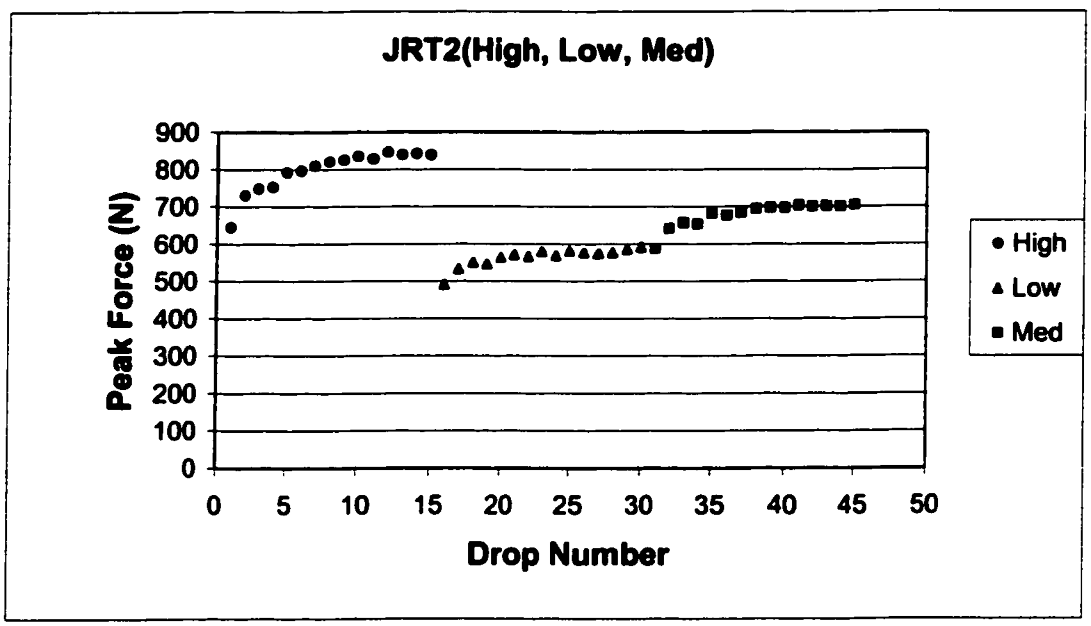
Miss Kim Fournier
Graduate Student
University of Windsor

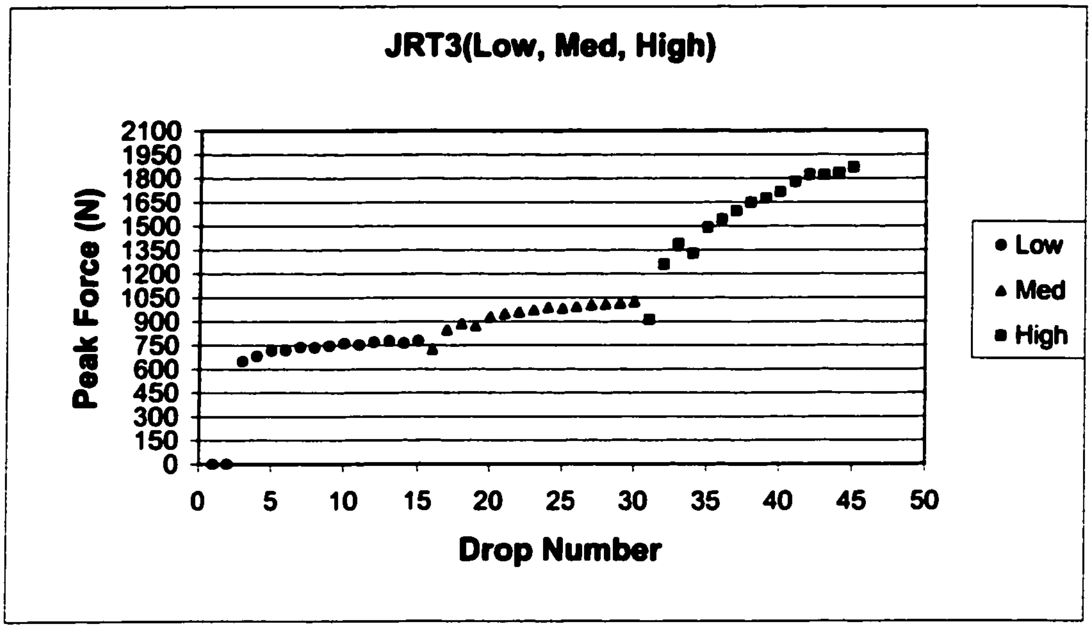
Appendix E. Schematic Representation of Dependent Variables.

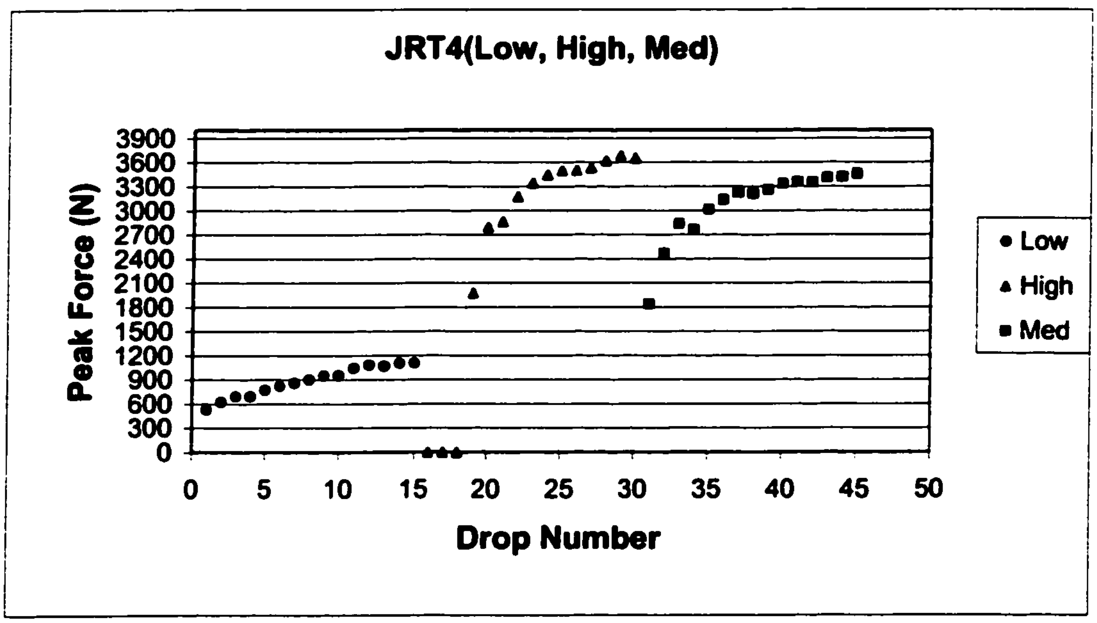


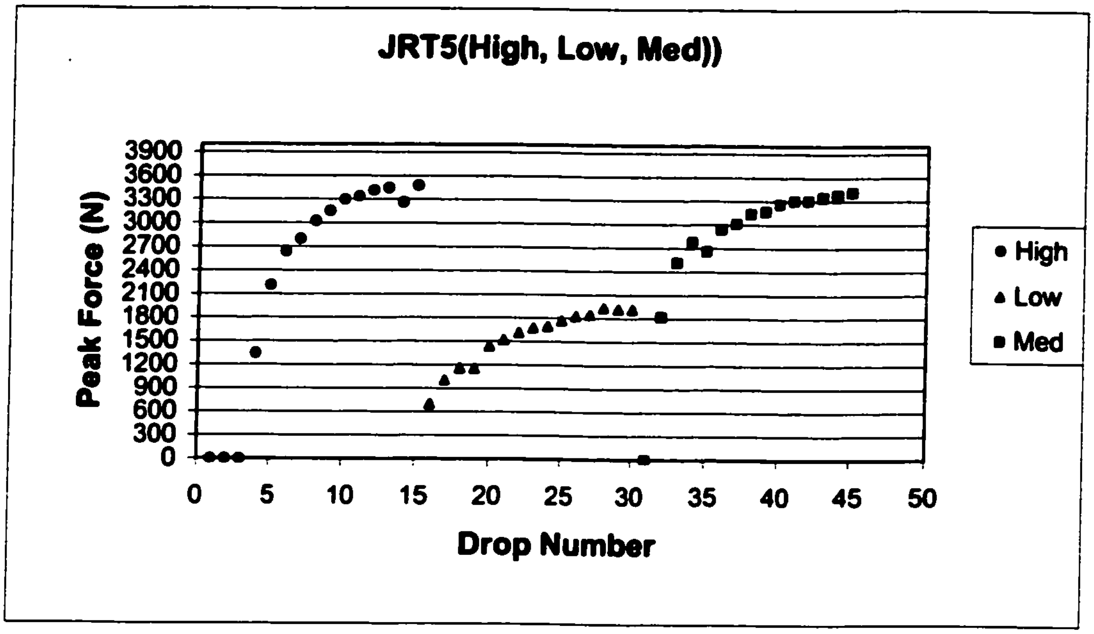
Appendix F. Peak Force Values for Three Impact Energy Levels in the Order They Were Delivered During the Experiment (Junior, Tibia Location).



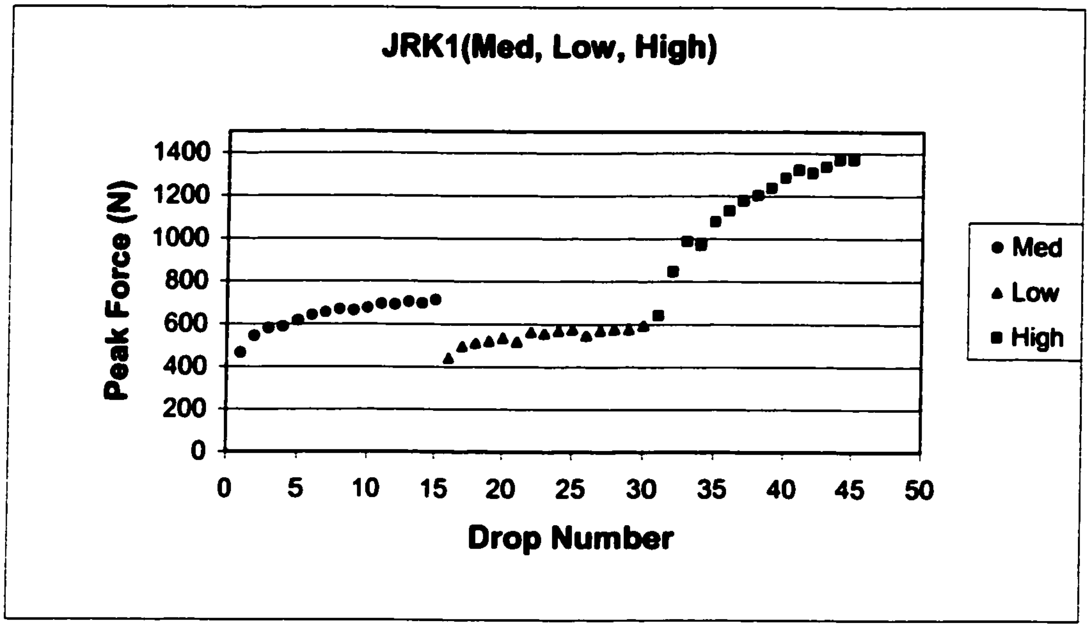


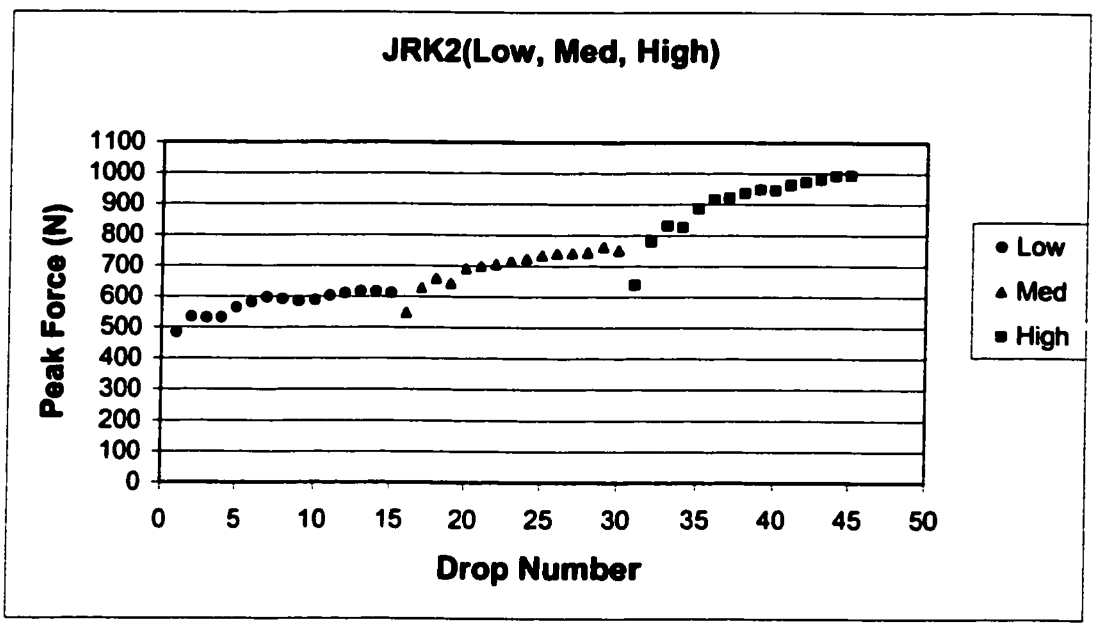

JRT3(Low, Med, High)
Peak Force (N)
2100
1950
1800
1650
1500
1350
1200
1050
900
750
600
450
300
150
0
0
5
10
15
20
25
30
35
40
45
50
Drop Number
Low
Med
High

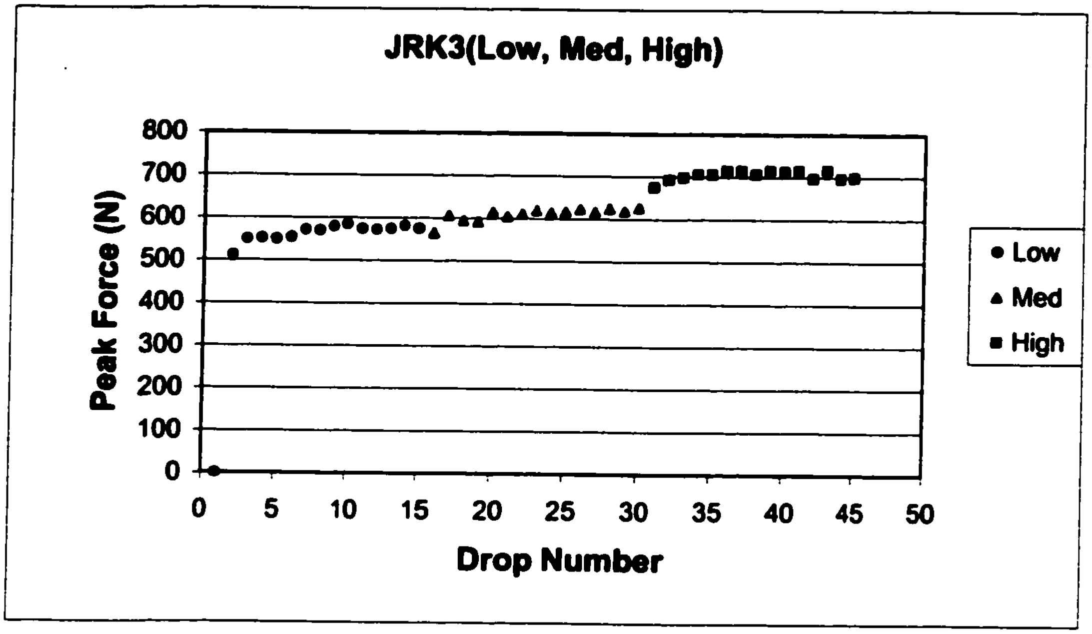

JRT4(Low, High, Med)
Peak Force (N)
3900
3600
3300
3000
2700
2400
2100
1800
1500
1200
900
600
300
0
0
5
10
15
20
25
30
35
40
45
50
Drop Number
Low
High
Med

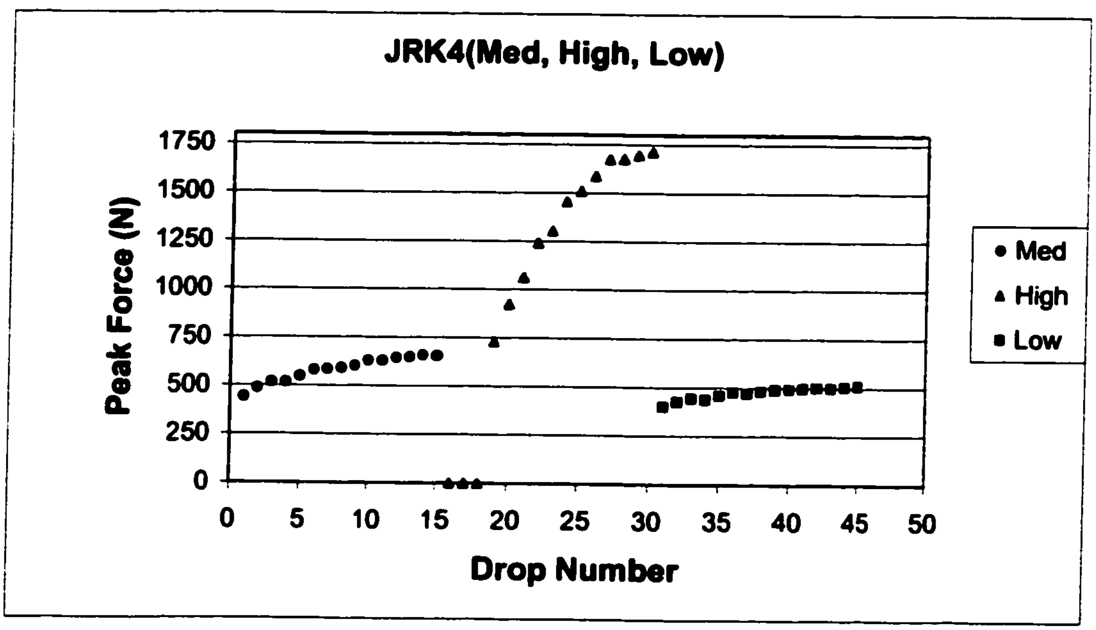

JRT5(High, Low, Med))
Peak Force (N)
3900
3600
3300
3000
2700
2400
2100
1800
1500
1200
900
600
300
0
0 5 10 15 20 25 30 35 40 45 50
Drop Number
High
Low
Med

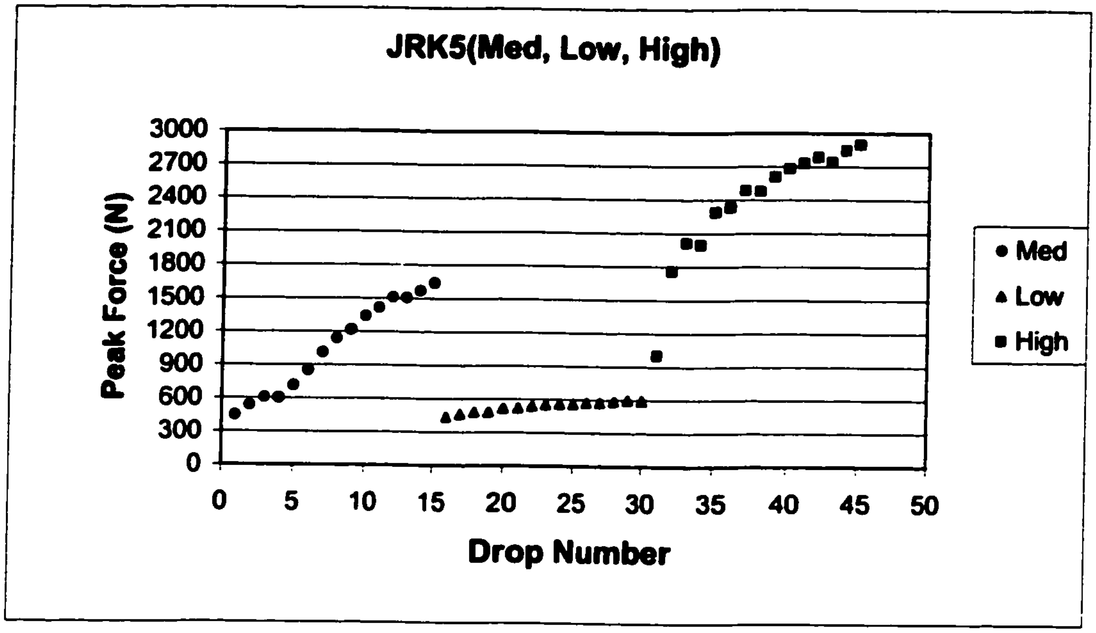
Appendix G. Peak Force Values for Three Impact Energy Levels in the Order They Were Delivered During the Experiment (Junior, Knee Location).



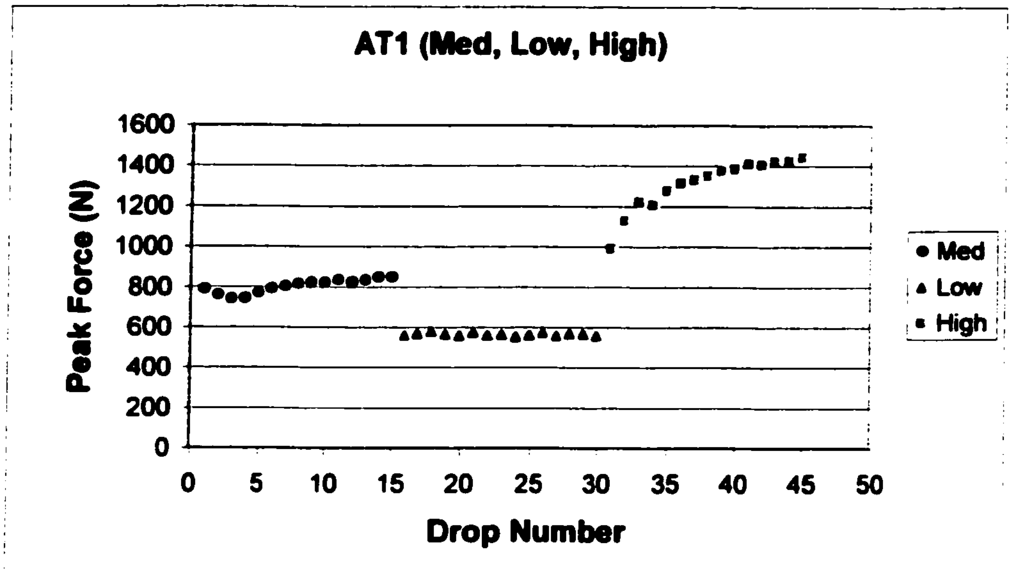


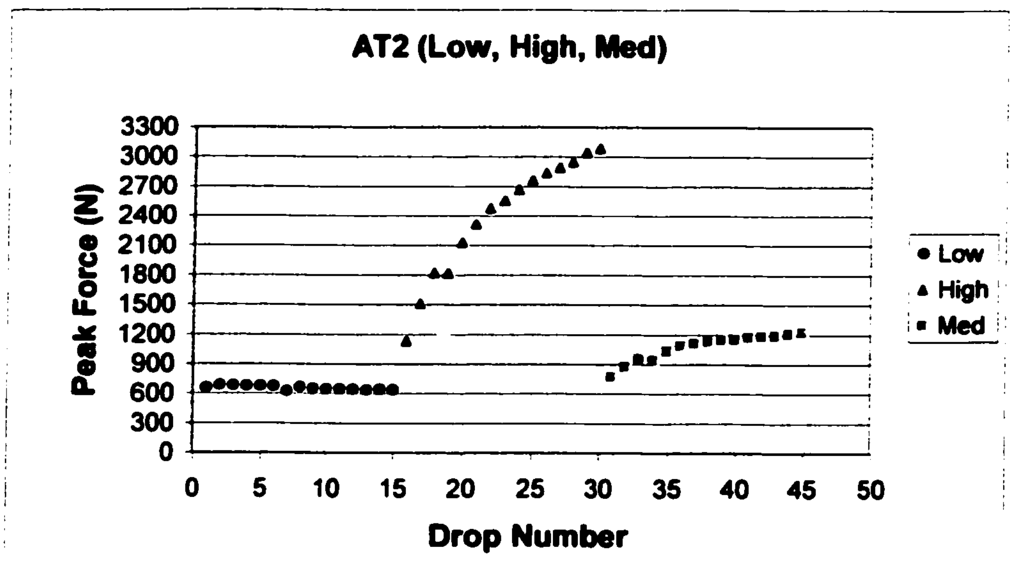

JRK3(Low, Med, High)
Peak Force (N)
800
700
600
500
400
300
200
100
0
0
5
10
15
20
25
30
35
40
45
50
Drop Number
Low
Med
High

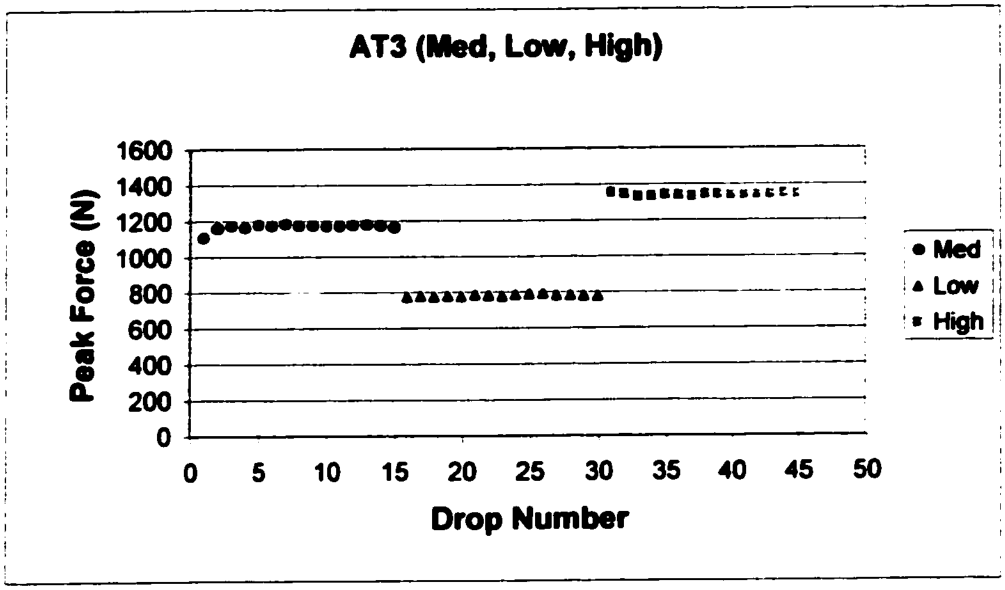

JRK4(Med, High, Low)
Peak Force (N)
1750
1500
1250
1000
750
500
250
0
0
5
10
15
20
25
30
35
40
45
50
Drop Number
Med
High
Low

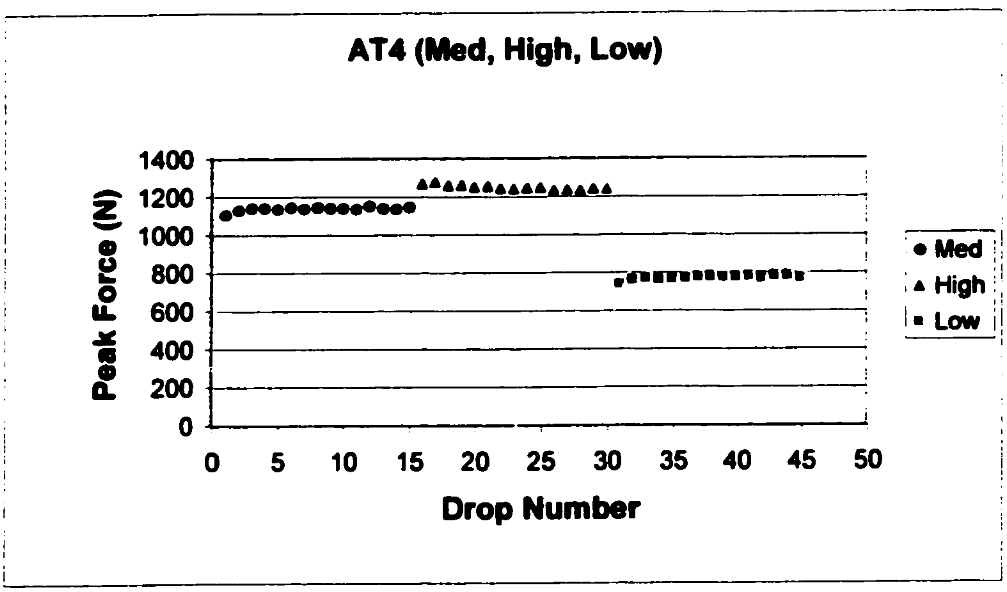

JRK5(Med, Low, High)
Peak Force (N)
3000
2700
2400
2100
1800
1500
1200
900
600
300
0
0
5
10
15
20
25
30
35
40
45
50
Drop Number
Med
Low
High

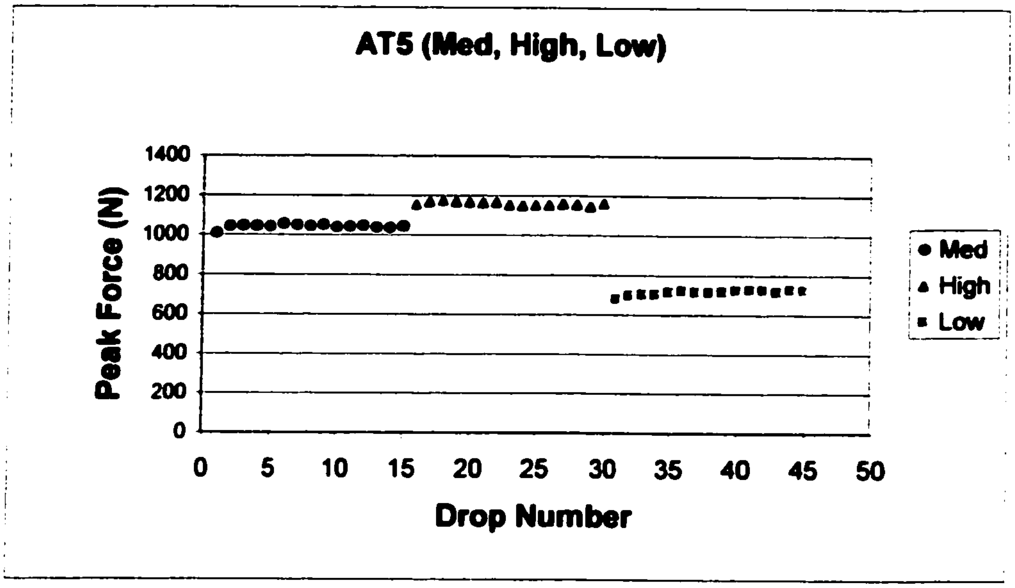
Appendix H. Peak Force Values for Three Impact Energy Levels in the Order They Were Delivered During the Experiment (Adult, Tibia Location).

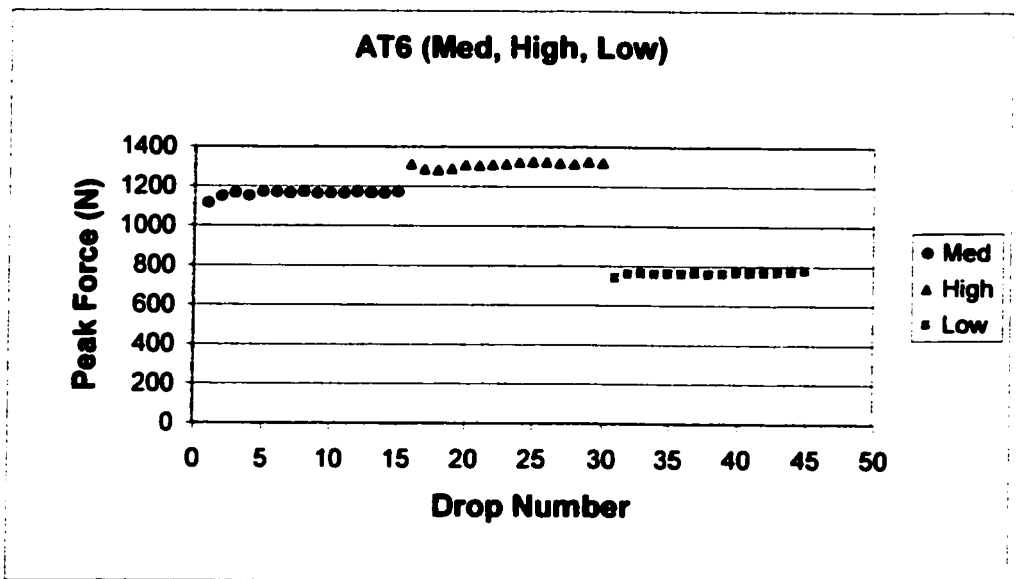


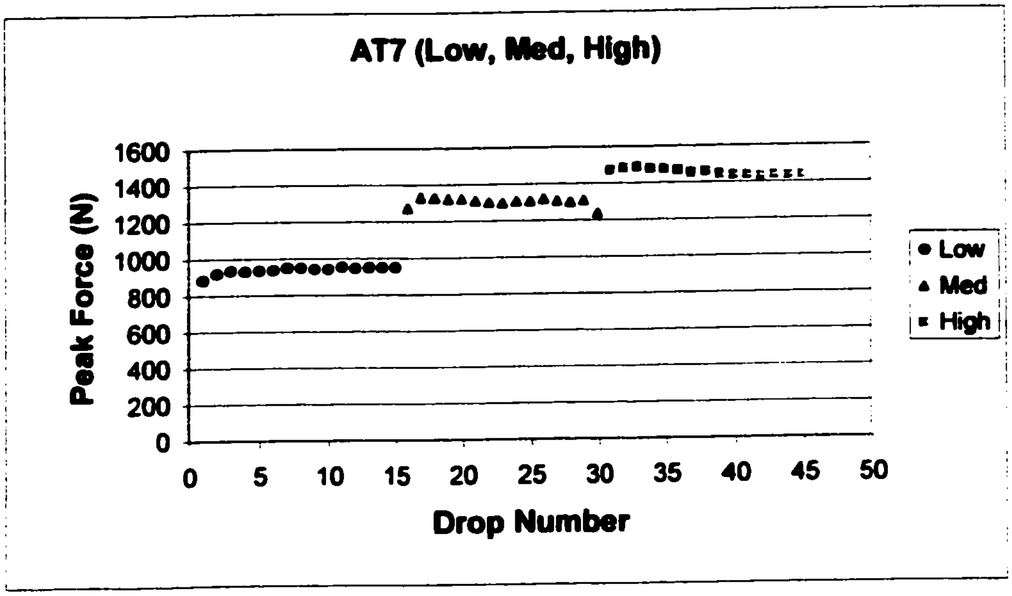


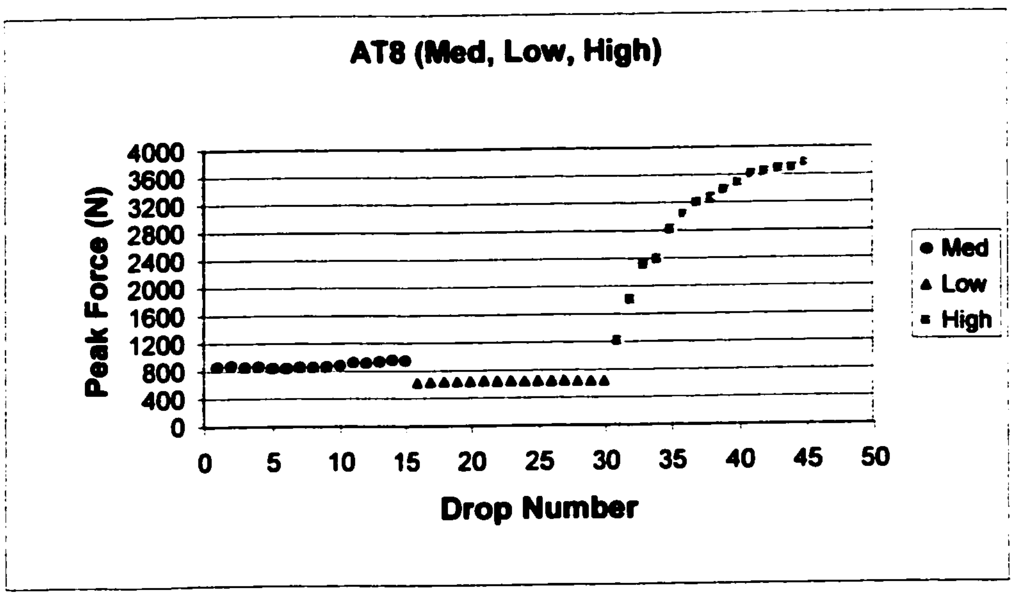

AT3 (Med, Low, High)
Peak Force (N)
1600
1400
1200
1000
800
600
400
200
0
0
5
10
15
20
25
30
35
40
45
50
Drop Number
Med
Low
High

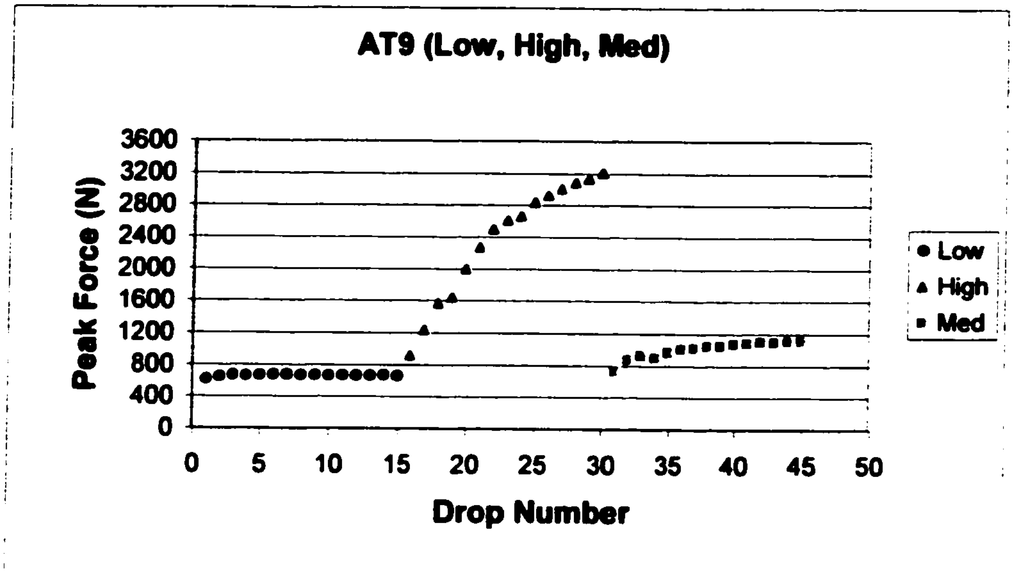

AT4 (Med, High, Low)
Peak Force (N)
1400
1200
1000
800
600
400
200
0
0
5
10
15
20
25
30
35
40
45
50
Drop Number
Med
High
Low


AT5 (Med, High, Low)
Peak Force (N)
1400
1200
1000
800
600
400
200
0
0 5 10 15 20 25 30 35 40 45 50
Drop Number
Med
High
Low

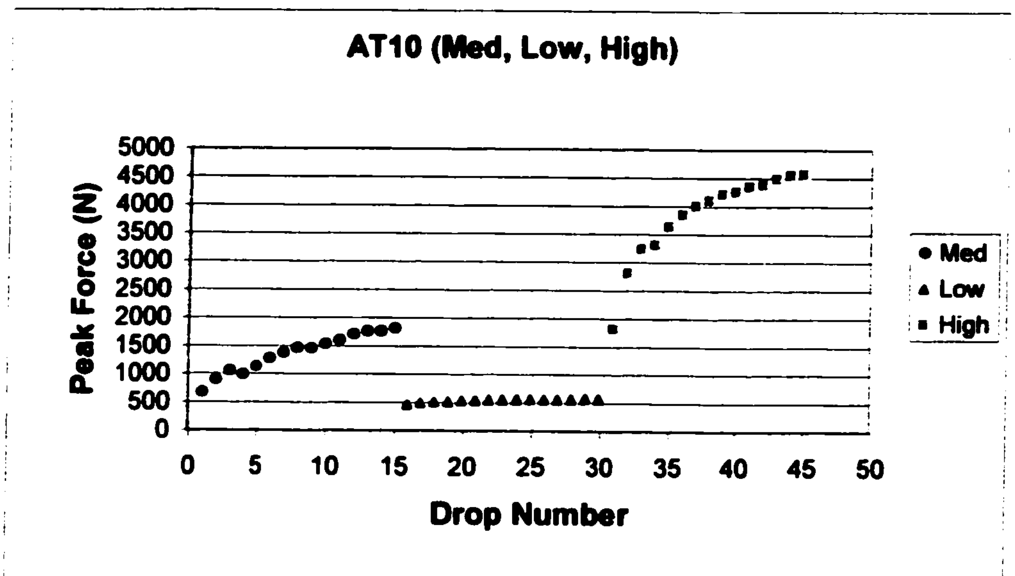

AT6 (Med, High, Low)
Peak Force (N)
1400
1200
1000
800
600
400
200
0
0 5 10 15 20 25 30 35 40 45 50
Drop Number
Med
High
Low


AT7 (Low, Med, High)
Peak Force (N)
1600
1400
1200
1000
800
600
400
200
0
0
5
10
15
20
25
30
35
40
45
50
Drop Number
Low
Med
High

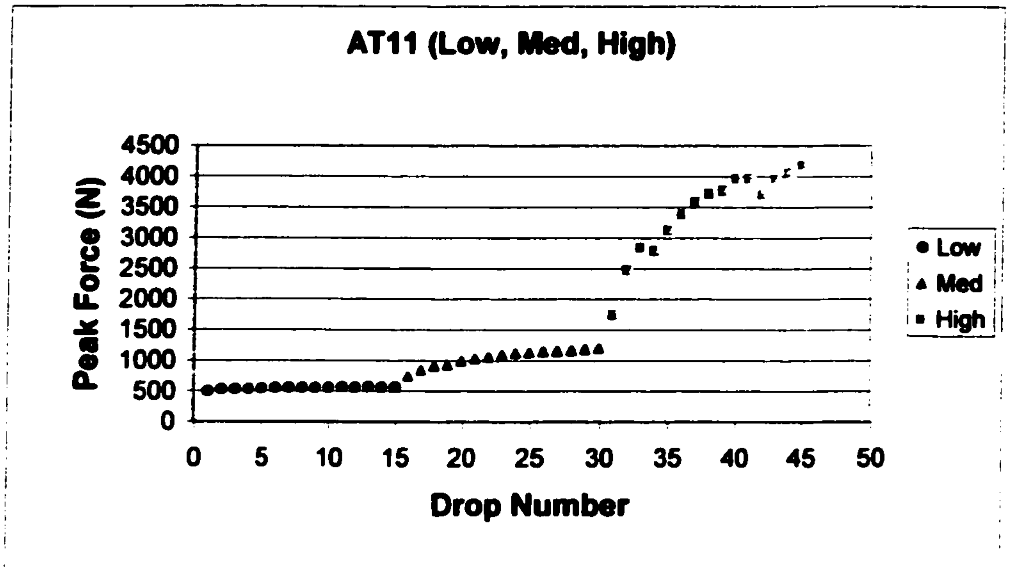

AT8 (Med, Low, High)
Peak Force (N)
4000
3600
3200
2800
2400
2000
1600
1200
800
400
0
0
5
10
15
20
25
30
35
40
45
50
Drop Number
Med
Low
High

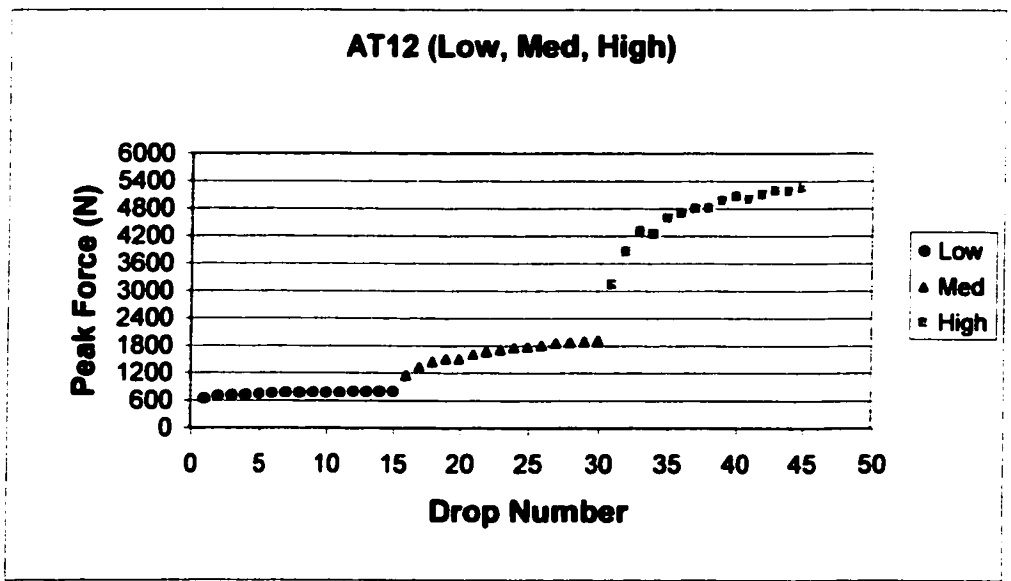


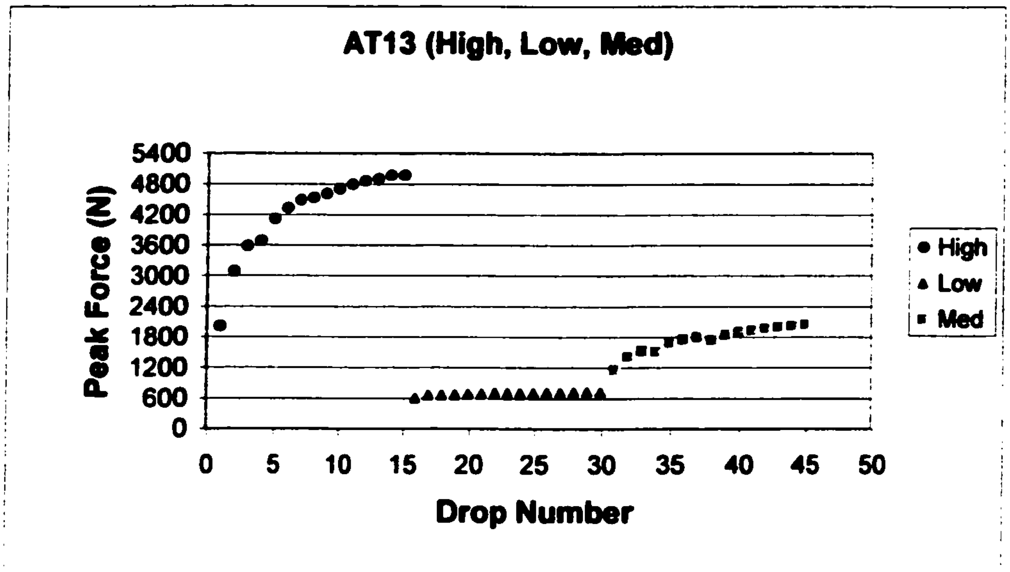
AT9 (Low, High, Med)
Peak Force (N)
3600
3200
2800
2400
2000
1600
1200
800
400
0
0
5
10
15
20
25
30
35
40
45
50
Drop Number
Low
High
Med

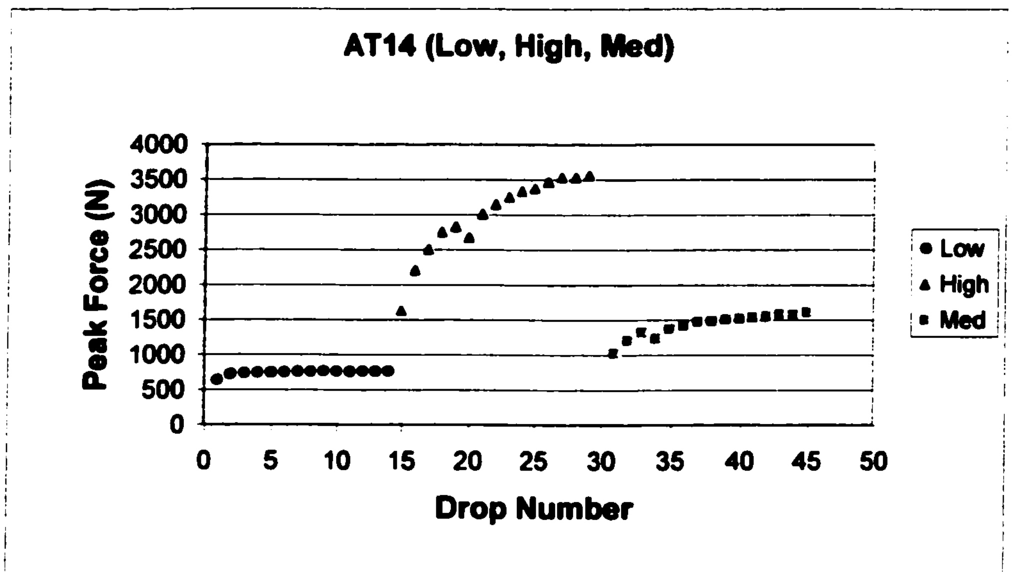


AT10 (Med, Low, High)
Peak Force (N)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
5
10
15
20
25
30
35
40
45
50
Drop Number
Med
Low
High

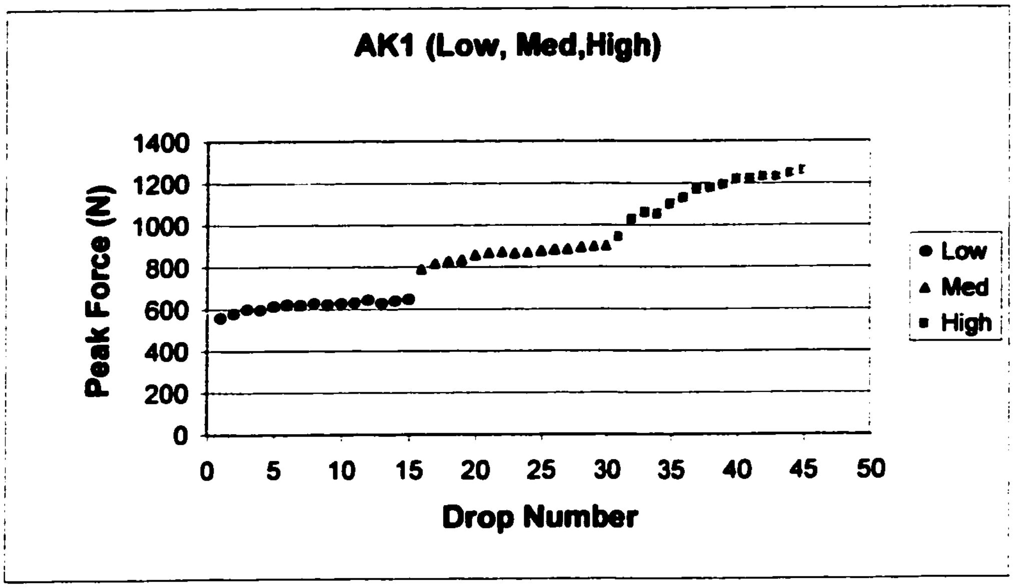

AT11 (Low, Med, High)
Peak Force (N)
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
5
10
15
20
25
30
35
40
45
50
Drop Number
Low
Med
High

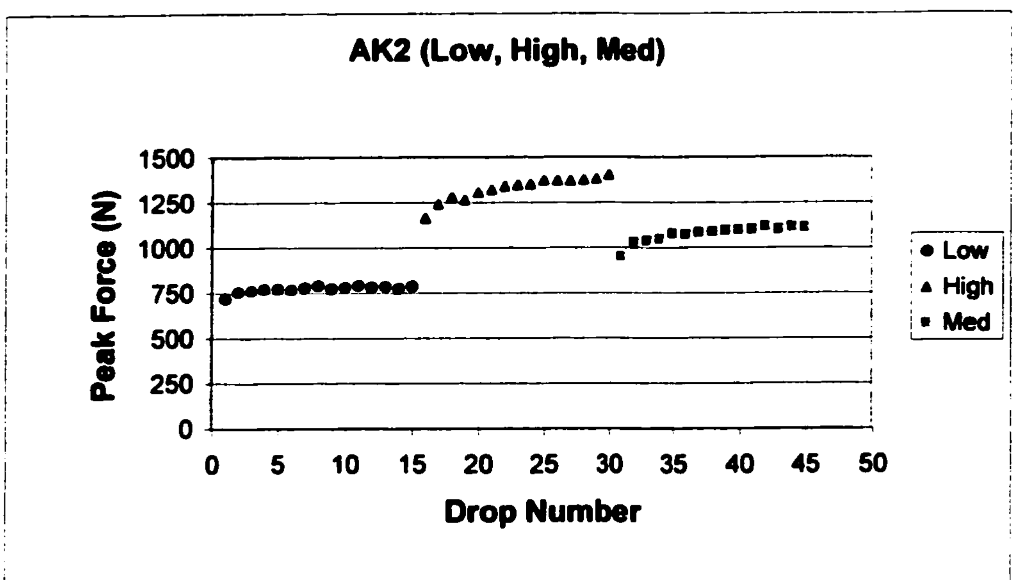

AT12 (Low, Med, High)
Peak Force (N)
6000
5400
4800
4200
3600
3000
2400
1800
1200
600
0
0
5
10
15
20
25
30
35
40
45
50
Drop Number
Low
Med
High

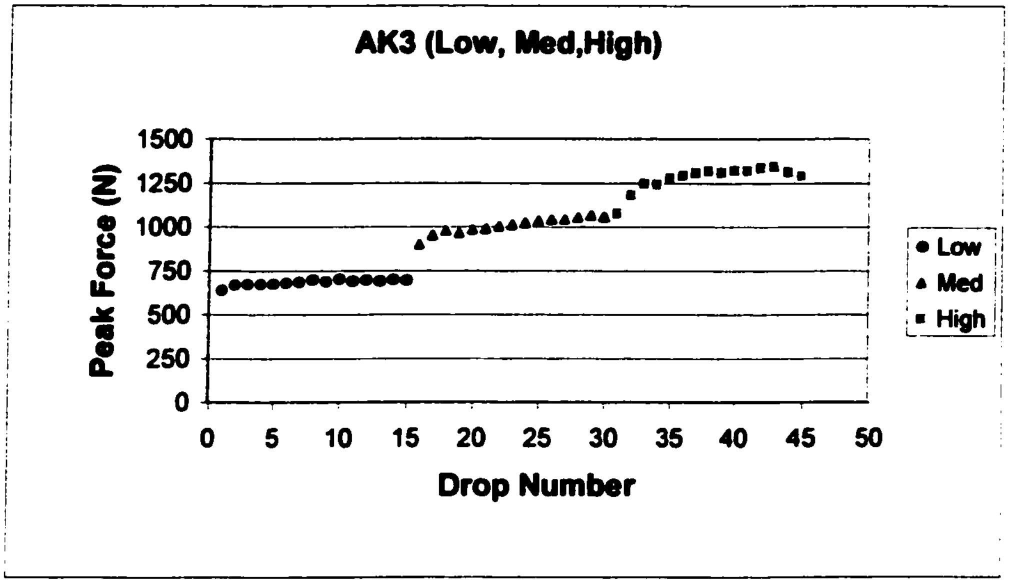

AT13 (High, Low, Med)
Peak Force (N)
5400
4800
4200
3600
3000
2400
1800
1200
600
0
0
5
10
15
20
25
30
35
40
45
50
Drop Number
High
Low
Med

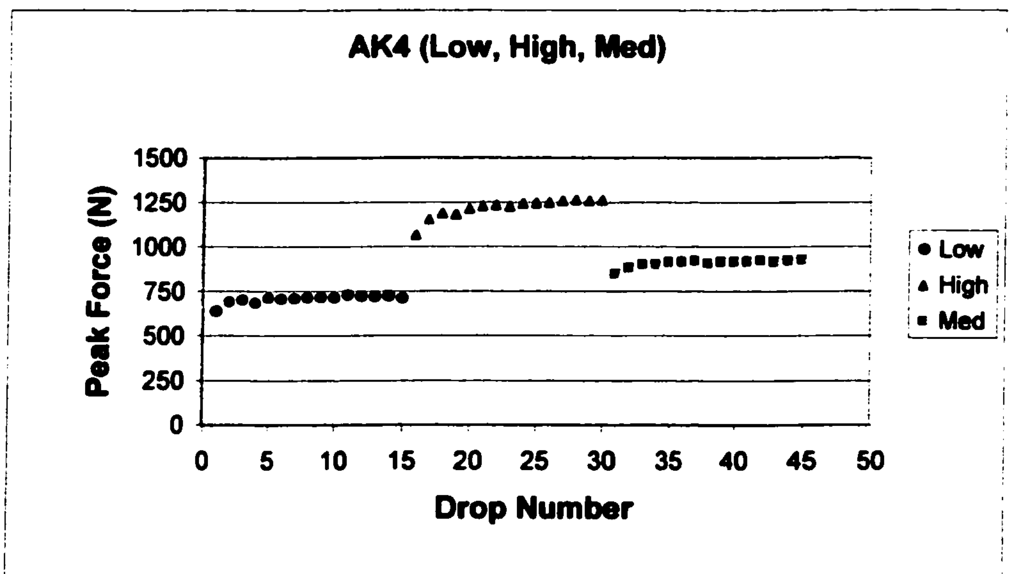

AT14 (Low, High, Med)
Peak Force (N)
4000
3500
3000
2500
2000
1500
1000
500
0
0
5
10
15
20
25
30
35
40
45
50
Drop Number
Low
High
Med

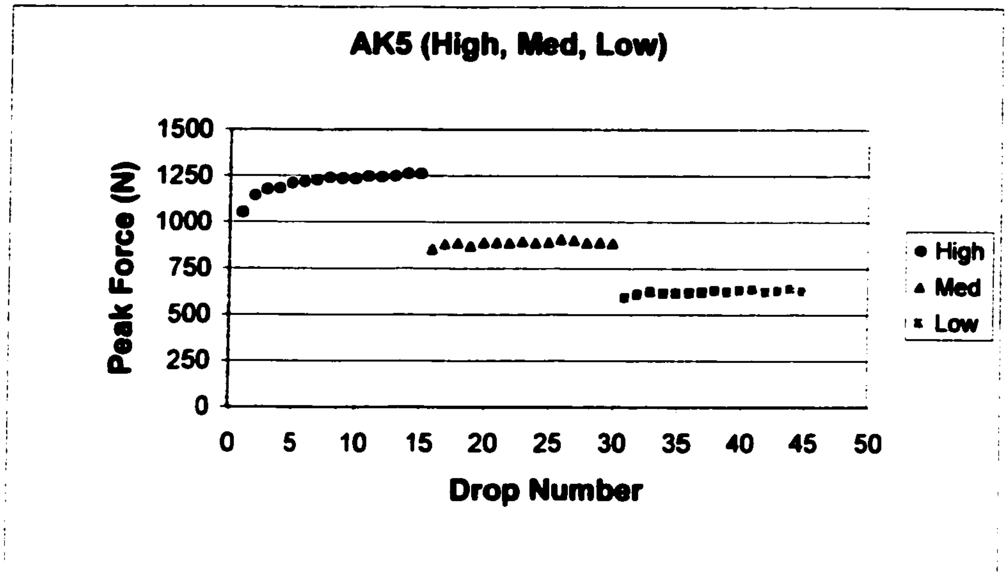
Appendix I. Peak Force Values for Three Impact Energy Levels in the Order They Were Delivered During the Experiment (Adult, Knee Location).

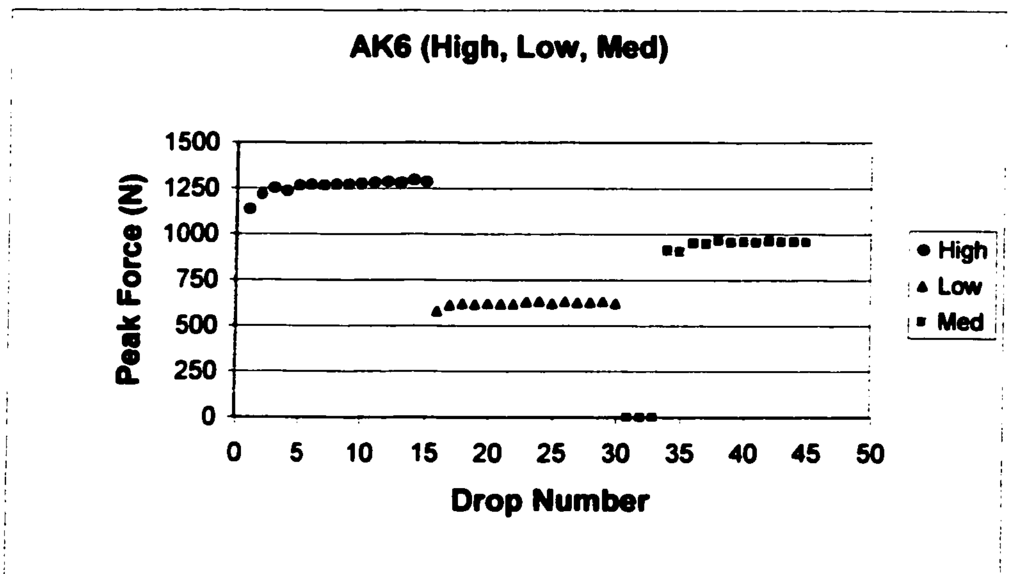


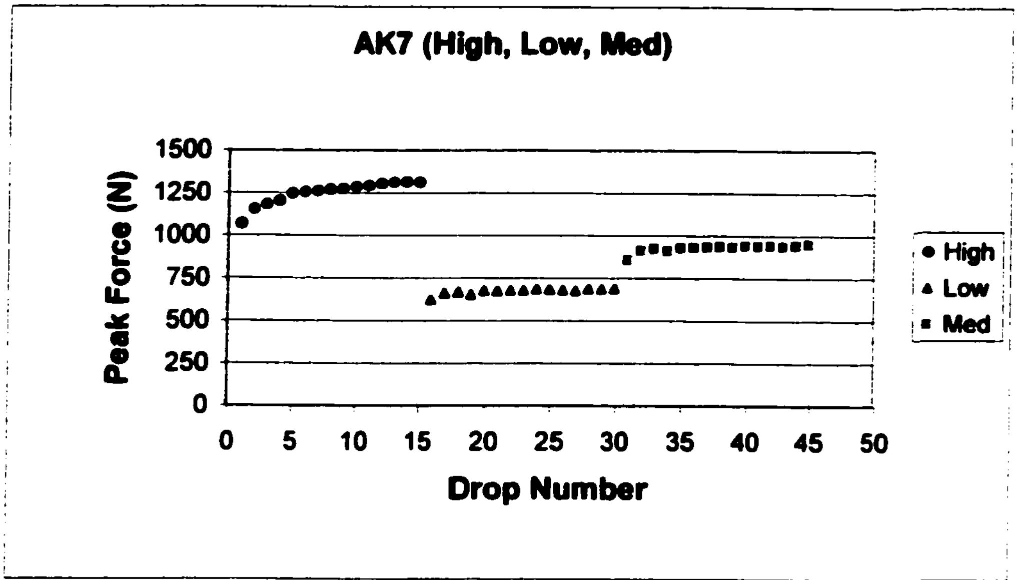


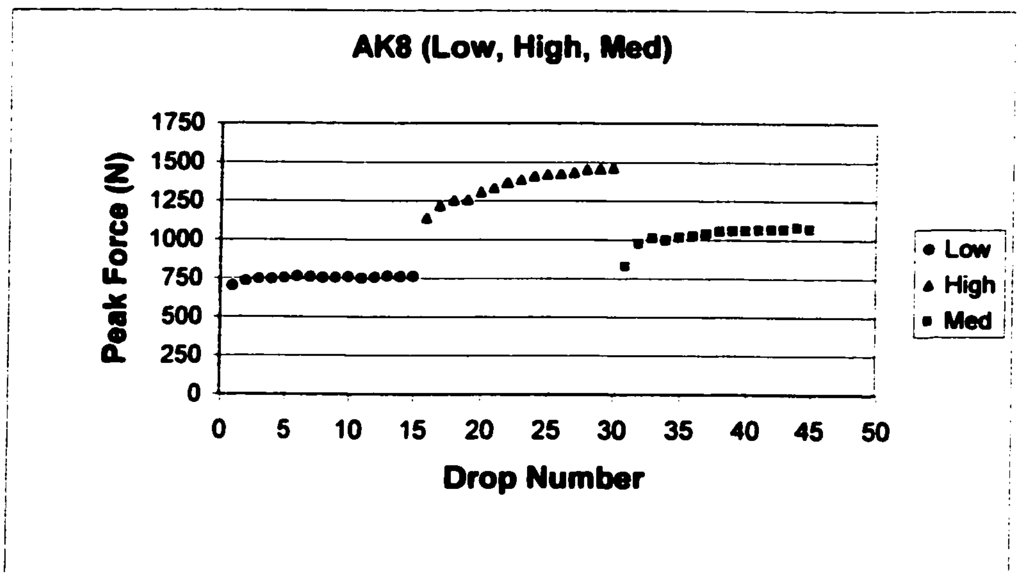

AK3 (Low, Med,High)
Peak Force (N)
1500
1250
1000
750
500
250
0
0 5 10 15 20 25 30 35 40 45 50
Drop Number
Low
Med
High

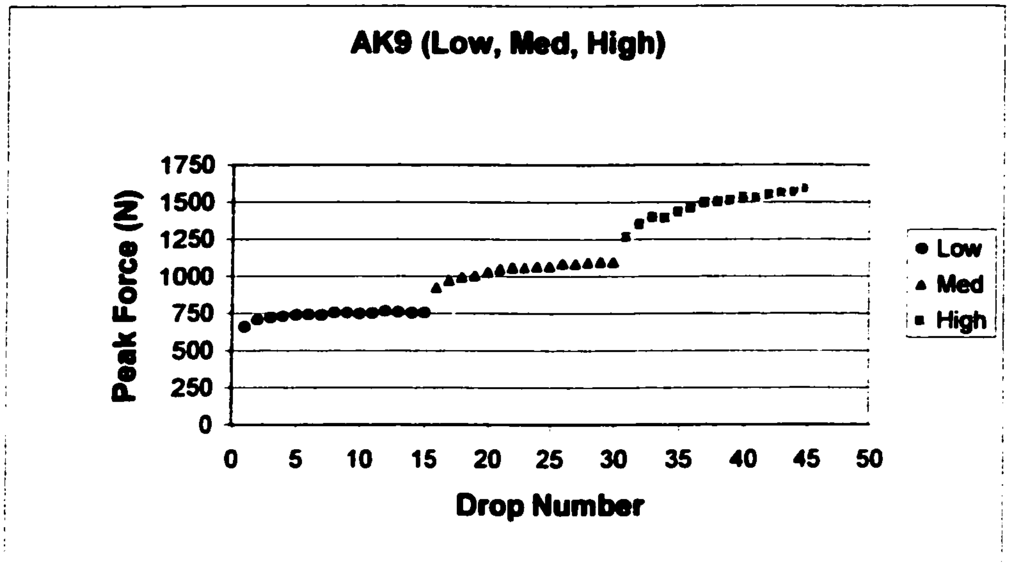

AK4 (Low, High, Med)
Peak Force (N)
1500
1250
1000
750
500
250
0
0 5 10 15 20 25 30 35 40 45 50
Drop Number
Low
High
Med


AK5 (High, Med, Low)
Peak Force (N)
1500
1250
1000
750
500
250
0
0 5 10 15 20 25 30 35 40 45 50
Drop Number
High
Med
Low

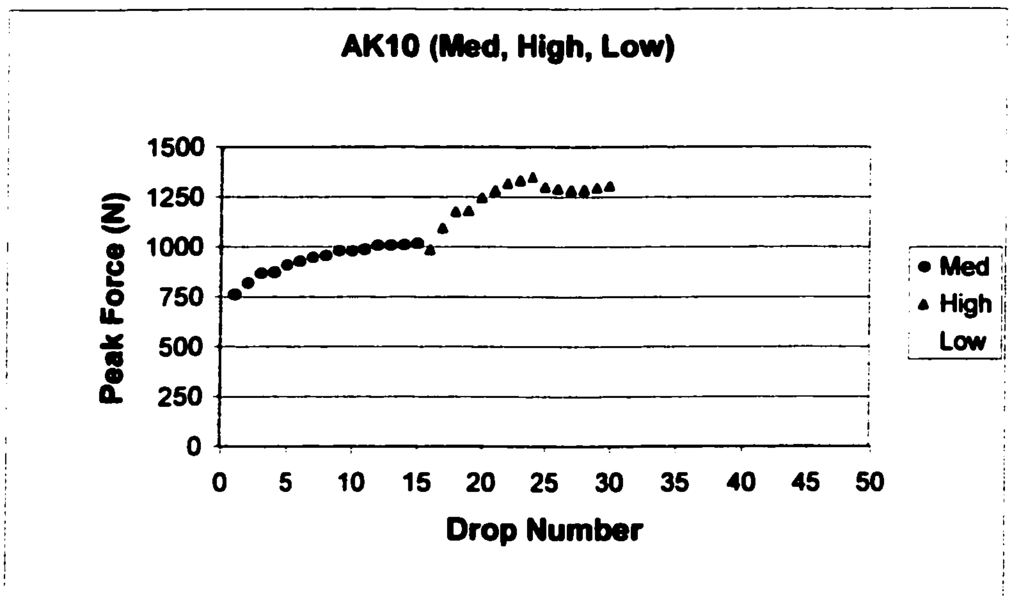

AK6 (High, Low, Med)
Peak Force (N)
1500
1250
1000
750
500
250
0
0 5 10 15 20 25 30 35 40 45 50
Drop Number
High
Low
Med


AK7 (High, Low, Med)
Peak Force (N)
1500
1250
1000
750
500
250
0
0
5
10
15
20
25
30
35
40
45
50
Drop Number
High
Low
Med

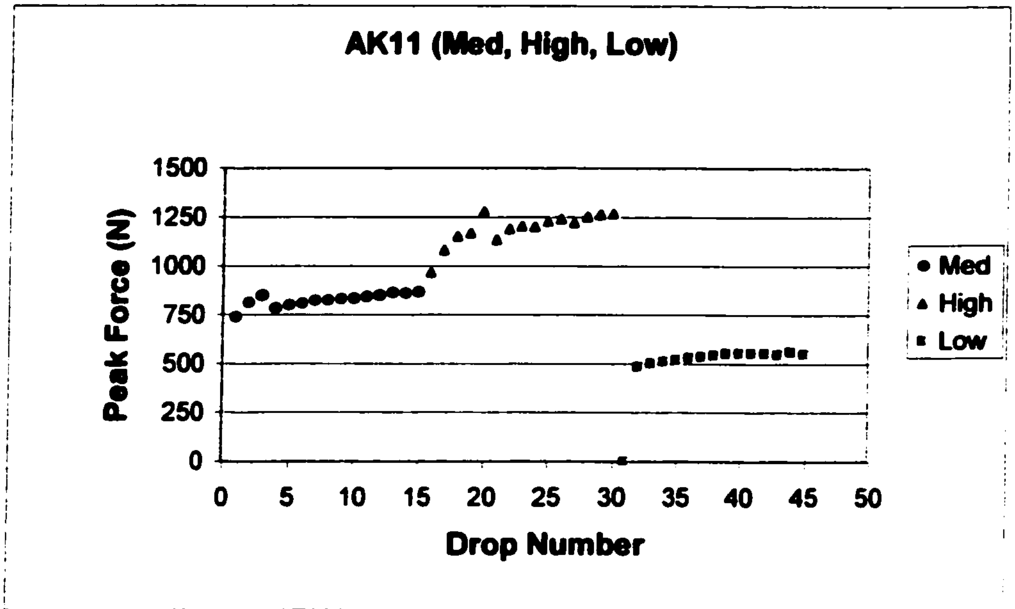

AK8 (Low, High, Med)
Peak Force (N)
1750
1500
1250
1000
750
500
250
0
0
5
10
15
20
25
30
35
40
45
50
Drop Number
Low
High
Med

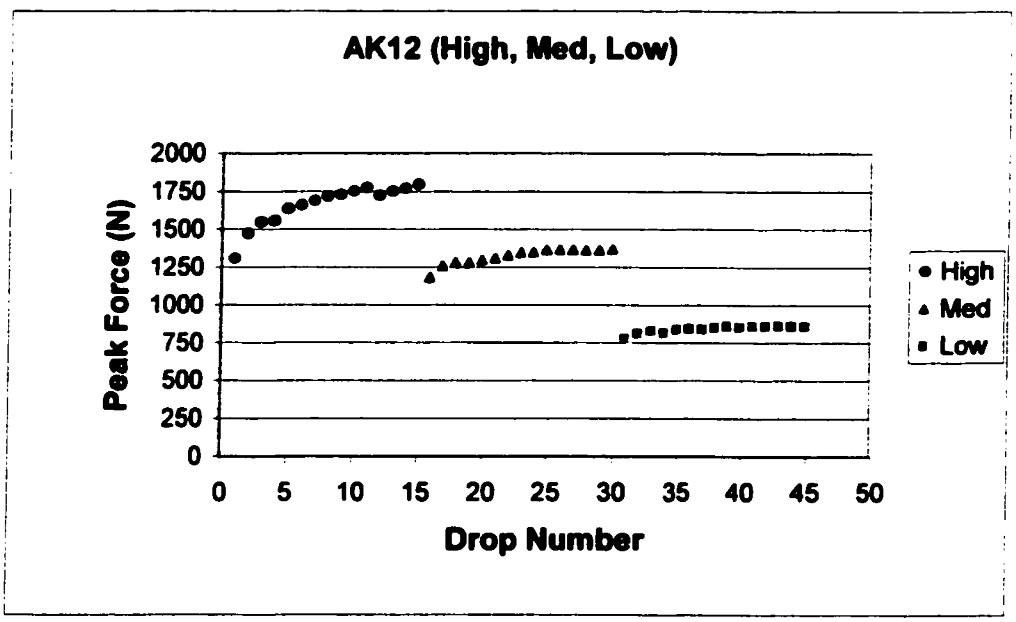


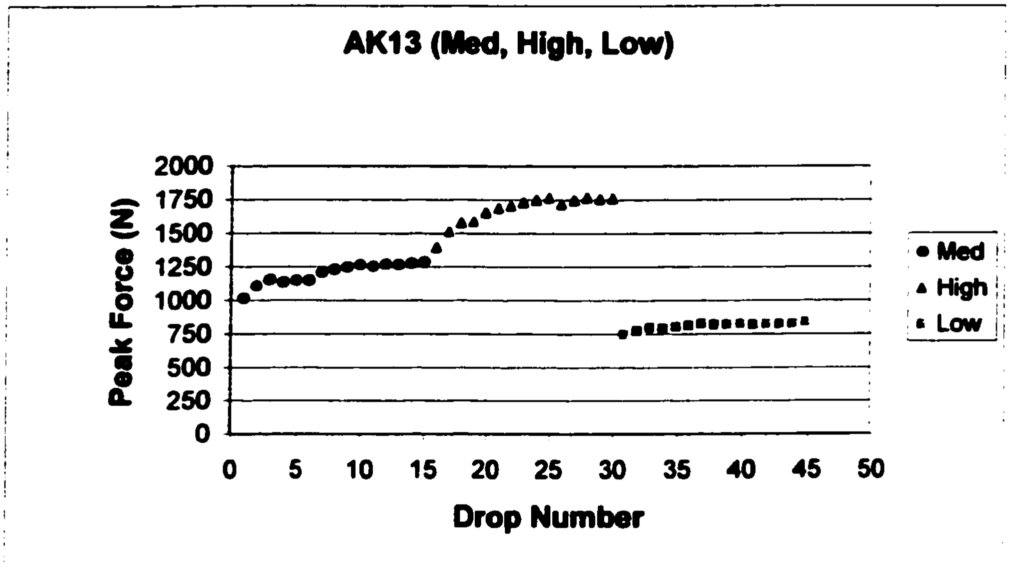
AK9 (Low, Med, High)
Peak Force (N)
1750
1500
1250
1000
750
500
250
0
0
5
10
15
20
25
30
35
40
45
50
Drop Number
Low
Med
High

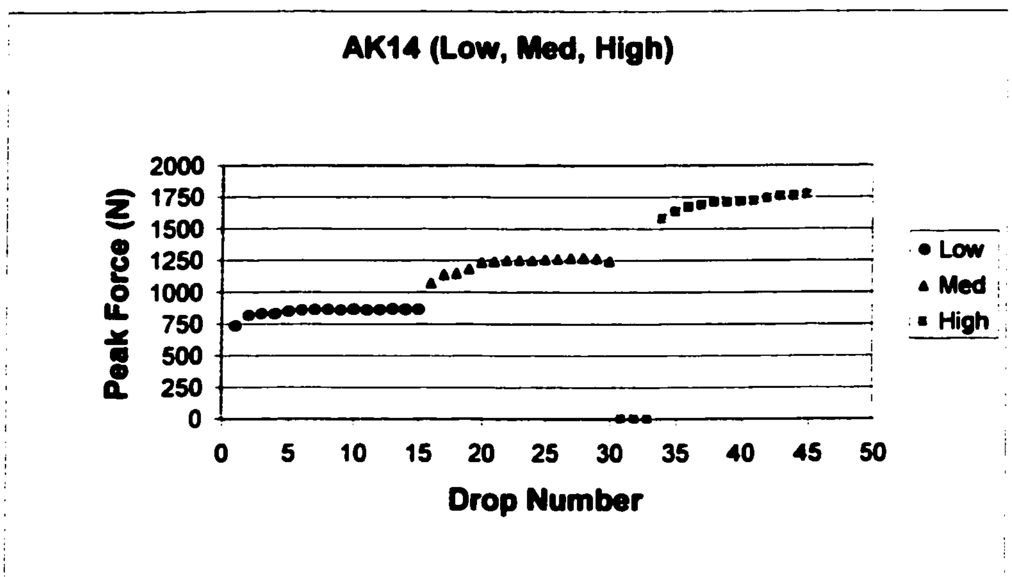


AK10 (Med, High, Low)
Peak Force (N)
1500
1250
1000
750
500
250
0
0
5
10
15
20
25
30
35
40
45
50
Drop Number
Med
High
Low


AK11 (Med, High, Low)
Peak Force (N)
1500
1250
1000
750
500
250
0
0
5
10
15
20
25
30
35
40
45
50
Drop Number
Med
High
Low


AK12 (High, Med, Low)
Peak Force (N)
2000
1750
1500
1250
1000
750
500
250
0
0
5
10
15
20
25
30
35
40
45
50
Drop Number
High
Med
Low


AK13 (Med, High, Low)
Peak Force (N)
2000
1750
1500
1250
1000
750
500
250
0
0 5 10 15 20 25 30 35 40 45 50
Drop Number
Med
High
Low


AK14 (Low, Med, High)
Peak Force (N)
2000
1750
1500
1250
1000
750
500
250
0
0 5 10 15 20 25 30 35 40 45 50
Drop Number
Low
Med
High

Appendix J. Means, Standard Deviations, and Coefficients of Variation for Junior Shin Guards (Tibia Location).

ImpactE	LOW							
3.23j	Baseline		Peak	TtoPeak	LdRate	Impulse	Eabsorb	%Eabsorb
		Mean	693.69	16.81	76167.82	6.59	2.64	81.73
		StdDev	15.26	0.20	4297.29	0.02	0.01	
		StdError	4.82	0.06	1358.92	0.01	0.00	
		CoVar	2.20	1.19	5.64	0.26	0.39	
	JRT1							
		Mean	620.50	12.43	75500.11	7.94	1.56	48.42
		StdDev	14.14	0.26	3818.51	0.03	0.03	
		StdError	4.08	0.08	1102.31	0.01	0.01	
		CoVar	2.28	2.11	5.06	0.44	2.22	
	JRT2							
		Mean	573.77	12.69	73579.50	7.88	1.62	50.19
		StdDev	11.80	0.40	3924.70	0.05	0.05	
		StdError	3.41	0.12	1132.96	0.01	0.01	
		CoVar	2.06	3.17	5.33	0.62	2.92	
	JRT3							
		Mean	745.00	11.20	115973.52	7.61	1.88	58.08
		StdDev	28.37	0.28	6522.90	0.08	0.07	
		StdError	8.19	0.08	1883.00	0.02	0.02	
		CoVar	3.81*	2.49	5.62	1.00	3.62	
	JRT4							
		Mean	947.60	11.00	83037.30	7.92	1.58	48.99
		StdDev	139.57	0.50	6261.34	0.03	0.03	
		StdError	40.29	0.14	1807.49	0.01	0.01	
		CoVar	14.73*	4.55	7.54	0.44	2.16	
	JRT5							
		Mean	1693.48	10.51	223966.47	8.04	1.46	45.05
		StdDev	233.24	0.43	100890.00	0.03	0.03	
		StdError	67.33	0.12	29124.43	0.01	0.01	
		CoVar	13.77*	4.06	45.05	0.38	2.19	

* Rejected based on CoVar >2.5%

ImpactE	MED							
4.07j	Baseline		Peak	TtoPeak	LdRate	Impulse	Eabsorb	%Eabsorb
		Mean	2250.87	11.28	1119605.22	7.61	3.17	77.93
		StdDev	149.99	0.25	272892.82	0.06	0.05	
		StdError	47.43	0.08	86296.29	0.02	0.01	
		CoVar	6.66	2.23	24.37	0.83	1.48	
	JRT1							
		Mean	672.19	12.66	87072.63	8.68	2.21	54.30
		StdDev	19.42	0.31	4375.82	0.06	0.06	
		StdError	5.61	0.09	1263.19	0.02	0.02	
		CoVar	2.89*	2.43	5.03	0.65	2.70	
	JRT2							
		Mean	691.29	11.36	87278.89	8.76	2.13	52.24
		StdDev	14.74	0.19	2920.22	0.04	0.04	
		StdError	4.26	0.06	843.00	0.01	0.01	
		CoVar	2.13	1.70	3.35	0.43	1.93	
	JRT3							
		Mean	975.02	9.93	137194.69	8.63	2.26	55.61
		StdDev	42.77	0.16	4015.20	0.05	0.05	
		StdError	12.35	0.05	1159.09	0.01	0.02	
		CoVar	4.39*	1.61	2.93	0.59	2.32	
	JRT4							
		Mean	3244.94	8.72	2220382.17	8.53	2.37	58.16
		StdDev	198.89	0.27	312990.93	0.02	0.02	
		StdError	57.42	0.08	90352.70	0.01	0.01	
		CoVar	6.13*	3.07	14.10	0.25	0.93	
	JRT5							
		Mean	3144.02	8.66	2034545.78	8.47	2.43	59.61
		StdDev	243.54	0.33	406014.59	0.02	0.02	
		StdError	70.30	0.10	117206.32	0.01	0.01	
		CoVar	7.75*	3.84	19.96	0.26	0.92	

* Rejected based on CoVar >2.5%

ImpactE	HIGH							
4.88j	Baseline		Peak	TtoPeak	LdRate	Impulse	Eabsorb	%Eabsorb
		Mean	4291.85	12.53	3886807.68	9.31	2.88	58.93
		StdDev	80.21	0.16	331569.36	0.05	0.05	
		StdError	25.36	0.05	104851.44	0.01	0.02	
		CoVar	1.87	1.28	8.53	0.50	1.77	
	JRT1							
		Mean	763.07	12.66	87849.97	9.54	2.61	53.52
		StdDev	14.20	0.16	3191.73	0.05	0.06	
		StdError	4.10	0.05	921.37	0.02	0.02	
		CoVar	1.86*	1.26	3.63	0.56	2.38	
	JRT2							
		Mean	818.99	12.60	110694.89	10.12	1.89	38.72
		StdDev	27.24	0.21	3872.10	0.07	0.09	
		StdError	7.86	0.06	1117.78	0.02	0.03	
		CoVar	3.33*	1.69	3.50	0.67	4.80	
	JRT3							
		Mean	1676.99	8.69	199914.97	9.30	2.88	59.12
		StdDev	164.41	0.28	21445.97	0.02	0.03	
		StdError	47.46	0.08	6190.92	0.01	0.01	
		CoVar	9.80*	3.20	10.73	0.24	0.87	
	JRT4							
		Mean	3244.94	8.72	2220382.17	8.53	2.37	48.51
		StdDev	198.89	0.27	312990.93	0.02	0.02	
		StdError	57.42	0.08	90352.70	0.01	0.01	
		CoVar	6.13*	3.07	14.10	0.25	0.93	
	JRT5							
		Mean	2950.58	8.42	1694831.31	9.24	2.95	60.46
		StdDev	632.50	0.93	747646.82	0.04	0.04	
		StdError	182.59	0.27	215827.05	0.01	0.01	
		CoVar	21.44*	11.00	44.11	0.38	1.30	

* Rejected based on CoVar >2.5%

Appendix K. Means, Standard Deviations, and Coefficients of Variation for Junior Shin Guards (Knee Location).

ImpactE	LOW							
3.23j	Baseline		Peak	TtoPeak	LdRate	Impulse	Eabsorb	%Eabsorb
		Mean	693.69	16.81	76167.82	6.59	2.64	81.73
		StdDev	15.26	0.20	4297.29	0.02	0.01	
		StdError	4.82	0.06	1358.92	0.01	0.00	
		CoVar	2.20	1.19	5.64	0.26	0.39	
	JRK1							
		Mean	559.14	13.53	49351.52	8.09	1.40	43.48
		StdDev	23.79	0.34	3295.22	0.04	0.04	
		StdError	6.87	0.10	951.25	0.01	0.01	
		CoVar	4.25*	2.48	6.68	0.46	2.79	
	JRK2							
		Mean	591.60	14.93	50897.44	8.40	1.06	32.93
		StdDev	24.67	0.26	2812.98	0.04	0.05	
		StdError	7.12	0.07	812.04	0.01	0.01	
		CoVar	4.1*	1.73	5.53	0.53	4.71	
	JRK3							
		Mean	570.19	12.18	72907.00	7.30	2.14	66.32
		StdDev	11.86	0.24	2498.87	0.06	0.05	
		StdError	3.42	0.07	721.36	0.02	0.01	
		CoVar	2.08	1.99	3.43	0.79	2.17	
	JRK4							
		Mean	485.54	15.16	44593.97	8.18	1.31	40.43
		StdDev	20.94	0.23	4034.44	0.03	0.03	
		StdError	6.04	0.07	1164.64	0.01	0.01	
		CoVar	4.31*	1.51	9.05	0.36	2.39	
	JRK5							
		Mean	555.66	14.76	45253.81	8.11	1.39	43.02
		StdDev	34.45	0.32	2210.38	0.03	0.03	
		StdError	9.94	0.09	638.08	0.01	0.01	
		CoVar	6.20*	2.17	4.88	0.40	2.48	

* Rejected based on CoVar >2.5%

ImpactE	MED							
4.07j	Baseline		Peak	TtoPeak	LdRate	Impulse	Eabsorb	%Eabsorb
		Mean	2250.87	11.28	1119605.22	7.61	3.17	77.93
		StdDev	149.99	0.25	272892.82	0.06	0.05	
		StdError	47.43	0.08	86296.29	0.02	0.01	
		CoVar	6.66	2.23	24.37	0.83	1.48	
	JRK1							
		Mean	668.06	14.44	58231.58	9.04	1.82	44.67
		StdDev	37.63	0.26	4294.76	0.07	0.08	
		StdError	10.86	0.08	1239.79	0.02	0.02	
		CoVar	5.63*	1.81	7.38	0.73	4.21	
	JRK2							
		Mean	720.83	13.06	63358.24	8.91	1.96	48.11
		StdDev	32.83	0.17	4053.88	0.04	0.05	
		StdError	9.48	0.05	1170.26	0.01	0.01	
		CoVar	4.55*	1.27	6.40	0.47	2.38	
	JRK3							
		Mean	614.96	12.71	75506.06	8.07	2.81	69.02
		StdDev	9.57	0.26	3737.14	0.03	0.03	
		StdError	2.76	0.07	1078.82	0.01	0.01	
		CoVar	1.56	2.03	4.95	0.40	1.01	
	JRK4							
		Mean	607.31	13.70	51945.90	8.89	1.99	48.78
		StdDev	45.00	0.35	1867.89	0.05	0.05	
		StdError	12.99	0.10	539.21	0.01	0.02	
		CoVar	7.41*	2.54	3.60	0.55	2.76	
	JRK5							
		Mean	1209.80	12.68	94746.25	9.02	1.84	45.12
		StdDev	349.03	0.82	52046.20	0.03	0.03	
		StdError	100.76	0.24	15024.44	0.01	0.01	
		CoVar	28.85*	6.44	54.93	0.30	1.70	

* Rejected based on CoVar >2.5%

ImpactE	HIGH							
4.88j	Baseline		Peak	TtoPeak	LdRate	Impulse	Eabsorb	%Eabsorb
		Mean	4291.85	12.53	3886807.68	9.31	2.08	42.53
		StdDev	80.21	0.16	331569.36	0.05	0.05	
		StdError	25.36	0.05	104851.44	0.01	0.02	
		CoVar	1.87	1.28	8.53	0.50	2.46	
	JRK1							
		Mean	1233.87	12.33	125343.24	9.78	2.33	47.76
		StdDev	124.69	0.43	19662.47	0.03	0.04	
		StdError	35.99	0.12	5676.07	0.01	0.01	
		CoVar	10.11*	3.50	15.69	0.31	1.61	
	JRK2							
		Mean	940.51	13.53	85895.24	9.84	2.25	46.16
		StdDev	48.73	0.25	8174.05	0.04	0.04	
		StdError	14.07	0.07	2359.65	0.01	0.01	
		CoVar	5.18*	1.87	9.52	0.36	1.97	
	JRK3							
		Mean	708.95	11.70	86926.08	8.80	3.40	69.73
		StdDev	7.50	0.13	3553.09	0.03	0.03	
		StdError	2.17	0.04	1025.69	0.01	0.01	
		CoVar	1.06	1.13	4.09	0.37	0.89	
	JRK4	JR4K						
		Mean	1380.89	11.97	105843.45	9.62	2.53	51.80
		StdDev	331.70	0.79	41005.92	0.03	0.04	
		StdError	95.75	0.23	11837.39	0.01	0.01	
		CoVar	24.02*	6.61	38.74	0.31	1.41	
	JRK5	JR5K						
		Mean	2575.66	11.15	1633149.38	9.40	2.78	57.05
		StdDev	265.87	0.52	544802.49	0.02	0.03	
		StdError	76.75	0.15	157270.93	0.01	0.01	
		CoVar	10.32*	4.63	33.36	0.24	0.93	

* Rejected based on CoVar >2.5%

Appendix L. Means, Standard Deviations, and Coefficients of Variation for Adult Shin Guards (Tibia Location).

ImpactE LOW								
6.47j	AT1		Peak	TtoPeak	LdRate	Impulse	Eabsorb	%Eabsorb
		Mean	565.17	8.87	110214.84	11.31	3.01	46.55
		StdDev	6.27	0.12	3257.21	0.16	0.23	
		StdError	1.81	0.04	940.27	0.05	0.07	
		CoVar	1.11	1.40	2.96	1.45	7.68	
	AT2							
		Mean	653.06	11.29	123501.11	10.98	3.46	53.50
		StdDev	17.61	0.50	5228.83	0.33	0.40	
		StdError	5.08	0.15	1509.43	0.10	0.12	
		CoVar	2.7*	4.46	4.23	3.04	11.69	
	AT3							
		Mean	783.17	10.13	132961.04	10.94	3.52	54.44
		StdDev	4.73	0.19	3695.58	0.04	0.06	
		StdError	1.37	0.05	1066.82	0.01	0.02	
		CoVar	0.60	1.84	2.78	0.40	1.66	
	AT4							
		Mean	777.34	10.36	122470.20	10.93	3.54	54.69
		StdDev	7.33	0.12	5370.88	0.04	0.06	
		StdError	2.12	0.03	1550.44	0.01	0.02	
		CoVar	0.94	1.15	4.39	0.40	1.65	
	AT5							
		Mean	720.44	12.50	125172.18	10.84	3.66	56.62
		StdDev	7.03	0.47	5805.47	0.04	0.06	
		StdError	2.03	0.14	1675.89	0.01	0.02	
		CoVar	0.98	3.75	4.64	0.40	1.52	
	AT6							
		Mean	765.52	10.13	119132.20	10.99	3.46	53.51
		StdDev	6.39	0.26	3559.77	0.04	0.06	
		StdError	1.84	0.08	1027.62	0.01	0.02	
		CoVar	0.83	2.60	2.99	0.39	1.65	
	AT7							
		Mean	944.00	10.27	172932.28	11.01	3.43	52.99
		StdDev	7.08	0.90	9275.99	0.03	0.04	
		StdError	2.04	0.26	2677.75	0.01	0.01	
		CoVar	0.75	8.77	5.36	0.28	1.24	

* Rejected Based on Coefficient of Variation > 2.5%

ImpactE LOW								
6.47j	AT8		Peak	TtoPeak	LdRate	Impulse	Eabsorb	%Eabsorb
		Mean	645.91	12.16	73106.34	11.26	3.08	47.63
		StdDev	5.39	0.23	3176.96	0.07	0.09	
		StdError	1.56	0.07	917.11	0.02	0.03	
		CoVar	0.83	1.87	4.35	0.58	3.00	
	AT9							
		Mean	667.87	10.22	73877.25	10.96	3.51	54.20
		StdDev	5.17	0.09	3373.95	0.07	0.09	
		StdError	1.49	0.03	973.98	0.02	0.03	
		CoVar	0.77	0.93	4.57	0.60	2.49	
	AT10							
		Mean	558.65	17.07	55406.17	10.96	3.50	54.03
		StdDev	16.13	0.52	3723.82	0.07	0.09	
		StdError	4.66	0.15	1074.97	0.02	0.03	
		CoVar	2.89*	3.02	6.72	0.63	2.62	
	AT11							
		Mean	558.61	18.14	87653.97	11.33	2.98	46.06
		StdDev	10.72	0.53	2985.65	0.08	0.12	
		StdError	3.10	0.15	861.88	0.02	0.03	
		CoVar	1.92	2.92	3.41	0.73	4.01	
	AT12							
		Mean	771.15	12.55	108723.07	11.43	2.84	43.87
		StdDev	22.12	0.17	17998.39	0.02	0.04	
		StdError	6.39	0.05	5195.69	0.01	0.01	
		CoVar	2.87*	1.32	16.55	0.21	1.24	
	AT13							
		Mean	710.22	13.17	120549.26	11.42	2.86	44.15
		StdDev	16.57	0.10	4224.09	0.04	0.07	
		StdError	4.78	0.03	1219.39	0.01	0.02	
		CoVar	2.33	0.79	3.50	0.39	2.29	
	AT14							
		Mean	755.88	10.26	110984.97	10.90	3.58	55.28
		StdDev	10.30	0.21	3010.84	0.11	0.14	
		StdError	2.97	0.06	869.16	0.03	0.04	
		CoVar	1.36	2.03	2.71	1.01	4.04	

*** Rejected Based on Coefficient of Variation > 2.5%**

ImpactE	MED							
12.94j	AT1		Peak	TtoPeak	LdRate	Impulse	Eabsorb	%Eabsorb
		Mean	814.86	16.85	122083.65	15.58	6.85	52.96
		StdDev	31.87	0.40	8174.68	0.07	0.14	
		StdError	9.20	0.12	2359.83	0.02	0.04	
		CoVar	3.91*	2.37	6.70	0.47	2.06	
	AT2							
		Mean	1133.50	14.54	75102.54	15.59	6.83	52.75
		StdDev	80.80	0.23	28857.26	0.07	0.14	
		StdError	23.33	0.07	8330.37	0.02	0.04	
		CoVar	7.13*	1.56	38.42	0.46	2.02	
	AT3							
		Mean	1172.13	9.94	228283.15	15.18	7.59	58.65
		StdDev	5.92	0.05	4940.23	0.08	0.14	
		StdError	1.71	0.02	1426.12	0.02	0.04	
		CoVar	0.51	0.55	2.16	0.51	1.83	
	AT4							
		Mean	1139.76	10.28	269208.65	14.96	7.99	61.71
		StdDev	5.65	0.05	8933.73	0.10	0.16	
		StdError	1.63	0.02	2578.95	0.03	0.05	
		CoVar	0.50	0.53	3.32	0.64	2.05	
	AT5							
		Mean	1044.45	10.24	237882.41	15.25	7.46	57.64
		StdDev	5.76	0.29	5028.88	0.13	0.24	
		StdError	1.66	0.08	1451.71	0.04	0.07	
		CoVar	0.55	2.85	2.11	0.86	3.16	
	AT6							
		Mean	1165.61	10.11	218822.99	15.11	7.73	59.70
		StdDev	5.80	0.09	3975.85	0.06	0.11	
		StdError	1.67	0.03	1147.73	0.02	0.03	
		CoVar	0.50	0.93	1.82	0.40	1.40	
	AT7							
		Mean	1303.75	9.55	407784.23	15.27	7.42	57.32
		StdDev	22.57	0.12	17166.88	0.29	0.51	
		StdError	6.52	0.03	4955.65	0.08	0.15	
		CoVar	1.73	1.22	4.21	1.92	6.93	

* Rejected Based on Coefficient of Variation > 2.5%

ImpactE	MED							
12.94j	AT8		Peak	TtoPeak	LdRate	Impulse	Eabsorb	%Eabsorb
		Mean	891.88	13.39	109462.97	15.58	6.84	52.87
		StdDev	39.56	2.02	11951.74	0.11	0.21	
		StdError	11.42	0.58	3450.17	0.03	0.06	
		CoVar	4.44*	15.07	10.92	0.70	3.05	
	AT9							
		Mean	1047.71	15.73	69017.70	15.36	7.26	56.09
		StdDev	65.57	0.29	3494.46	0.06	0.11	
		StdError	18.93	0.08	1008.76	0.02	0.03	
		CoVar	6.26*	1.87	5.06	0.40	1.56	
	AT10							
		Mean	1490.99	13.98	122901.90	14.93	8.03	62.03
		StdDev	262.62	0.73	31065.52	0.19	0.32	
		StdError	75.81	0.21	8967.84	0.05	0.09	
		CoVar	17.61*	5.23	25.28	1.26	3.94	
	AT11							
		Mean	1104.78	15.41	86866.44	15.50	7.00	54.11
		StdDev	82.94	0.37	11148.67	0.04	0.08	
		StdError	23.94	0.11	3218.34	0.01	0.02	
		CoVar	7.51*	2.39	12.83	0.29	1.20	
	AT12							
		Mean	1743.32	12.11	146505.13	15.36	7.26	56.09
		StdDev	140.59	0.22	13075.12	0.02	0.04	
		StdError	40.58	0.06	3774.46	0.01	0.01	
		CoVar	8.06*	1.85	8.92	0.14	0.56	
	AT13							
		Mean	1851.90	12.03	154023.26	15.43	7.13	55.13
		StdDev	158.99	0.30	17403.15	0.03	0.05	
		StdError	45.90	0.09	5023.86	0.01	0.01	
		CoVar	8.59*	2.50	11.30	0.16	0.66	
	AT14							
		Mean	1489.22	12.17	207878.98	15.23	7.50	57.93
		StdDev	104.04	0.25	13831.25	0.10	0.17	
		StdError	30.03	0.07	3992.74	0.03	0.05	
		CoVar	6.99*	2.07	6.65	0.63	2.29	

* Rejected Based on Coefficient of Variation > 2.5%

ImpactE HIGH								
19.41j	AT1		Peak	TtoPeak	LdRate	Impulse	Eabsorb	%Eabsorb
		Mean	1362.92	15.06	103883.81	18.71	11.14	57.41
		StdDev	70.50	0.33	3532.68	0.05	0.11	
		StdError	20.35	0.10	1019.80	0.01	0.03	
		CoVar	5.17*	2.19	3.40	0.27	1.02	
	AT2							
		Mean	2629.01	12.65	248865.12	18.47	11.66	60.09
		StdDev	386.91	0.52	81216.45	0.05	0.10	
		StdError	111.69	0.15	23445.17	0.01	0.03	
		CoVar	14.72*	4.12	32.63	0.26	0.89	
	AT3							
		Mean	1340.24	9.03	276481.17	18.80	10.93	56.33
		StdDev	5.12	0.09	6385.35	0.08	0.19	
		StdError	1.48	0.03	1843.29	0.02	0.05	
		CoVar	0.38	0.97	2.31	0.44	1.70	
	AT4							
		Mean	1243.72	8.81	311981.41	18.73	11.09	57.13
		StdDev	8.95	0.17	4324.38	0.12	0.27	
		StdError	2.58	0.05	1248.34	0.04	0.08	
		CoVar	0.72	1.89	1.39	0.66	2.47	
	AT5							
		Mean	1158.83	8.05	266675.66	18.65	11.27	58.04
		StdDev	8.02	0.14	9533.87	0.12	0.26	
		StdError	2.31	0.04	2752.19	0.03	0.07	
		CoVar	0.69	1.71	3.58	0.63	2.29	
	AT6							
		Mean	1315.22	9.43	264264.37	18.79	10.94	56.39
		StdDev	10.77	0.11	5175.80	0.10	0.22	
		StdError	3.11	0.03	1494.13	0.03	0.06	
		CoVar	0.82	1.14	1.96	0.51	1.97	
	AT7							
		Mean	1449.60	9.46	536564.34	18.87	10.77	55.50
		StdDev	16.94	0.07	6541.94	0.09	0.20	
		StdError	4.89	0.02	1888.50	0.02	0.06	
		CoVar	1.17	0.75	1.22	0.46	1.83	

* Rejected Based on Coefficient of Variation > 2.5%

ImpactE HIGH								
19.41j	AT8		Peak	TtoPeak	LdRate	Impulse	Eabsorb	%Eabsorb
		Mean	3333.94	12.06	527879.44	18.36	11.90	61.29
		StdDev	418.38	0.44	172766.25	0.03	0.06	
		StdError	120.78	0.13	49873.32	0.01	0.02	
		CoVar	12.55*	3.63	32.73	0.16	0.52	
	AT9							
		Mean	2659.85	13.65	277710.46	18.23	12.17	62.69
		StdDev	484.16	0.53	111366.01	0.03	0.07	
		StdError	139.76	0.15	32148.60	0.01	0.02	
		CoVar	18.20*	3.92	40.10	0.17	0.54	
	AT10							
		Mean	4146.18	11.20	971706.94	17.74	13.17	67.86
		StdDev	384.97	0.43	347850.22	0.03	0.05	
		StdError	111.13	0.12	100415.71	0.01	0.02	
		CoVar	9.28*	3.86	35.80	0.15	0.40	
	AT11							
		Mean	3686.81	11.81	614117.55	18.02	12.60	64.94
		StdDev	411.10	0.40	237125.46	0.04	0.09	
		StdError	118.67	0.12	68452.22	0.01	0.03	
		CoVar	11.15*	3.41	38.61	0.25	0.72	
	AT12							
		Mean	4914.37	9.50	2030660.64	17.84	12.98	66.85
		StdDev	293.77	0.23	563229.39	0.04	0.08	
		StdError	84.80	0.07	162590.32	0.01	0.02	
		CoVar	5.98*	2.47	27.74	0.23	0.63	
	AT13							
		Mean	4580.21	9.97	1425337.09	18.04	12.56	64.71
		StdDev	386.04	0.40	507321.91	0.06	0.13	
		StdError	111.44	0.12	146451.22	0.02	0.04	
		CoVar	8.43*	4.04	35.59	0.36	1.04	
	AT14							
		Mean	3207.91	11.20	557593.96	18.19	12.25	63.12
		StdDev	320.61	0.29	99869.97	0.05	0.11	
		StdError	92.55	0.08	28829.98	0.02	0.03	
		CoVar	9.99*	2.62	17.91	0.30	0.93	

* Rejected Based on Coefficient of Variation > 2.5%

Appendix M. Means, Standard Deviations, and Coefficients of Variation for Adult Shin Guards (Knee Location).

ImpactE	LOW							
6.47j	AK1		Peak	TtoPeak	LdRate	Impulse	Eabsorb	%Eabsorb
		Mean	625.73	14.31	63982.70	10.96	3.49	54.01
		StdDev	13.76	0.80	2719.90	0.08	0.10	
		StdError	3.97	0.23	785.17	0.02	0.03	
		CoVar	2.20	5.62	4.25	0.70	2.93	
	AK2							
		Mean	778.34	12.11	89418.80	10.51	4.07	62.96
		StdDev	6.98	0.08	2106.12	0.09	0.11	
		StdError	2.01	0.02	607.99	0.03	0.03	
		CoVar	0.90	0.67	2.36	0.86	2.66	
	AK3							
		Mean	689.20	13.13	71985.07	10.27	4.35	67.27
		StdDev	9.72	0.35	3293.45	0.17	0.19	
		StdError	2.80	0.10	950.74	0.05	0.05	
		CoVar	1.41	2.69	4.58	1.64	4.28	
	AK4							
		Mean	712.96	13.77	74322.96	10.23	4.40	68.01
		StdDev	11.14	0.32	2655.32	0.06	0.07	
		StdError	3.21	0.09	766.52	0.02	0.02	
		CoVar	1.56	2.29	3.57	0.59	1.50	
	AK5							
		Mean	625.88	13.13	54401.46	10.08	4.56	70.54
		StdDev	8.25	0.47	1571.68	0.02	0.02	
		StdError	2.38	0.14	453.71	0.00	0.01	
		CoVar	1.32	3.58	2.89	0.17	0.40	
	AK6							
		Mean	627.27	14.87	72740.65	9.87	4.78	73.95
		StdDev	6.16	0.25	2504.60	0.05	0.05	
		StdError	1.78	0.07	723.02	0.01	0.01	
		CoVar	0.98	1.65	3.44	0.50	1.04	
	AK7							
		Mean	680.90	12.67	76906.88	9.81	4.84	74.81
		StdDev	9.71	0.55	2926.56	0.02	0.02	
		StdError	2.80	0.16	844.82	0.01	0.01	
		CoVar	1.43	4.30	3.81	0.20	0.40	

* Rejected Based on Coefficient of Variation > 2.5%

ImpactE LOW								
6.47j	AK8		Peak	TtoPeak	LdRate	Impulse	Eabsorb	%Eabsorb
		Mean	757.90	12.87	71436.13	10.82	3.68	56.91
		StdDev	5.08	0.35	2417.22	0.08	0.10	
		StdError	1.47	0.10	697.79	0.02	0.03	
		CoVar	0.67	2.70	3.38	0.70	2.66	
	AK9							
		Mean	749.63	13.47	74897.89	10.51	4.07	62.91
		StdDev	10.37	0.47	3079.05	0.08	0.09	
		StdError	2.99	0.14	888.84	0.02	0.03	
		CoVar	1.38	3.51	4.11	0.72	2.23	
	AK10							
		Mean	603.64	14.43	51192.72	10.33	4.29	66.32
		StdDev	9.41	1.05	2291.05	0.04	0.05	
		StdError	2.72	0.30	661.37	0.01	0.01	
		CoVar	1.56	7.26	4.48	0.40	1.11	
	AK11							
		Mean	544.62	15.40	39110.82	10.07	4.57	70.64
		StdDev	15.00	1.12	2051.47	0.06	0.06	
		StdError	4.33	0.32	592.21	0.02	0.02	
		CoVar	2.75*	7.25	5.25	0.59	1.38	
	AK12							
		Mean	850.26	12.42	107162.97	10.46	4.13	63.81
		StdDev	13.75	0.27	4463.43	0.05	0.06	
		StdError	3.97	0.08	1288.48	0.02	0.02	
		CoVar	1.62	2.21	4.17	0.50	1.50	
	AK13							
		Mean	821.40	13.19	87503.38	10.32	4.29	66.38
		StdDev	13.51	0.16	3667.02	0.05	0.05	
		StdError	3.90	0.05	1058.58	0.01	0.02	
		CoVar	1.64	1.20	4.19	0.45	1.23	
	AK14							
		Mean	857.59	12.76	103895.95	10.37	4.24	65.51
		StdDev	10.13	0.27	6603.69	0.05	0.05	
		StdError	2.92	0.08	1906.32	0.01	0.02	
		CoVar	1.18	2.08	6.36	0.44	1.24	

* Rejected Based on Coefficient of Variation > 2.5%

ImpactE	MED							
12.94j	AK1		Peak	TtoPeak	LdRate	Impulse	Eabsorb	%Eabsorb
		Mean	877.14	14.95	90484.01	15.02	7.88	60.92
		StdDev	18.98	0.68	4218.91	0.06	0.11	
		StdError	5.48	0.20	1217.89	0.02	0.03	
		CoVar	2.16	4.54	4.66	0.40	1.34	
	AK2							
		Mean	1093.24	12.19	140884.76	14.65	8.51	65.74
		StdDev	20.99	0.10	5895.99	0.04	0.07	
		StdError	6.06	0.03	1702.02	0.01	0.02	
		CoVar	1.92	0.81	4.18	0.30	0.85	
	AK3							
		Mean	1023.14	11.99	151101.63	13.30	10.44	80.65
		StdDev	31.87	0.29	10967.94	0.07	0.09	
		StdError	9.20	0.08	3166.17	0.02	0.03	
		CoVar	3.11*	2.38	7.26	0.53	0.83	
	AK4							
		Mean	916.86	14.66	95986.47	13.79	9.81	75.80
		StdDev	7.16	0.25	2797.06	0.02	0.03	
		StdError	2.07	0.07	807.44	0.01	0.01	
		CoVar	0.78	1.72	2.91	0.16	0.31	
	AK5							
		Mean	891.56	13.36	85502.57	13.53	10.15	78.42
		StdDev	8.86	0.16	2490.06	0.06	0.07	
		StdError	2.56	0.05	718.82	0.02	0.02	
		CoVar	0.99	1.20	2.91	0.42	0.73	
	AK6							
		Mean	950.89	14.33	114588.54	13.82	9.76	75.39
		StdDev	20.49	0.14	4510.34	0.19	0.25	
		StdError	5.92	0.04	1302.02	0.05	0.07	
		CoVar	2.16	0.94	3.94	1.36	2.55	
	AK7							
		Mean	935.85	13.79	112079.02	13.81	9.78	75.54
		StdDev	10.57	0.38	2070.97	0.04	0.05	
		StdError	3.05	0.11	597.84	0.01	0.01	
		CoVar	1.13	2.73	1.85	0.26	0.51	

* Rejected Based on Coefficient of Variation > 2.5%

ImpactE	MED							
12.94j	AK8		Peak	TtoPeak	LdRate	Impulse	Eabsorb	%Eabsorb
		Mean	1049.91	14.25	84590.25	14.92	8.05	62.21
		StdDev	24.98	0.19	2695.95	0.08	0.13	
		StdError	7.21	0.06	778.25	0.02	0.04	
		CoVar	2.38	1.36	3.19	0.52	1.64	
	AK9							
		Mean	1067.83	13.58	97621.40	14.95	8.00	61.83
		StdDev	28.91	0.36	3078.05	0.08	0.15	
		StdError	8.35	0.11	888.56	0.02	0.04	
		CoVar	2.71*	2.68	3.15	0.57	1.82	
	AK10							
		Mean	966.46	14.28	65148.73	14.76	8.32	64.32
		StdDev	45.23	0.11	2112.06	0.16	0.27	
		StdError	13.06	0.03	609.70	0.05	0.08	
		CoVar	4.68*	0.80	3.24	1.09	3.19	
	AK11							
		Mean	833.15	15.27	55935.75	14.40	8.90	68.76
		StdDev	25.88	1.32	3415.28	0.06	0.09	
		StdError	7.47	0.38	985.91	0.02	0.03	
		CoVar	3.11*	8.67	6.11	0.41	1.04	
	AK12							
		Mean	1342.30	11.72	132388.20	14.86	8.16	63.06
		StdDev	30.93	0.25	1924.85	0.10	0.18	
		StdError	8.93	0.07	555.66	0.03	0.05	
		CoVar	2.30	2.10	1.45	0.70	2.17	
	AK13							
		Mean	1229.42	11.88	145441.36	14.43	8.84	68.35
		StdDev	54.60	0.26	3400.38	0.25	0.38	
		StdError	15.76	0.07	981.60	0.07	0.11	
		CoVar	4.44*	2.17	2.34	1.75	4.34	
	AK14							
		Mean	1250.71	11.25	135668.04	14.58	8.62	66.63
		StdDev	24.24	0.75	3226.34	0.15	0.24	
		StdError	7.00	0.22	931.36	0.04	0.07	
		CoVar	1.94	6.71	2.38	1.05	2.79	

*** Rejected Based on Coefficient of Variation > 2.5%**

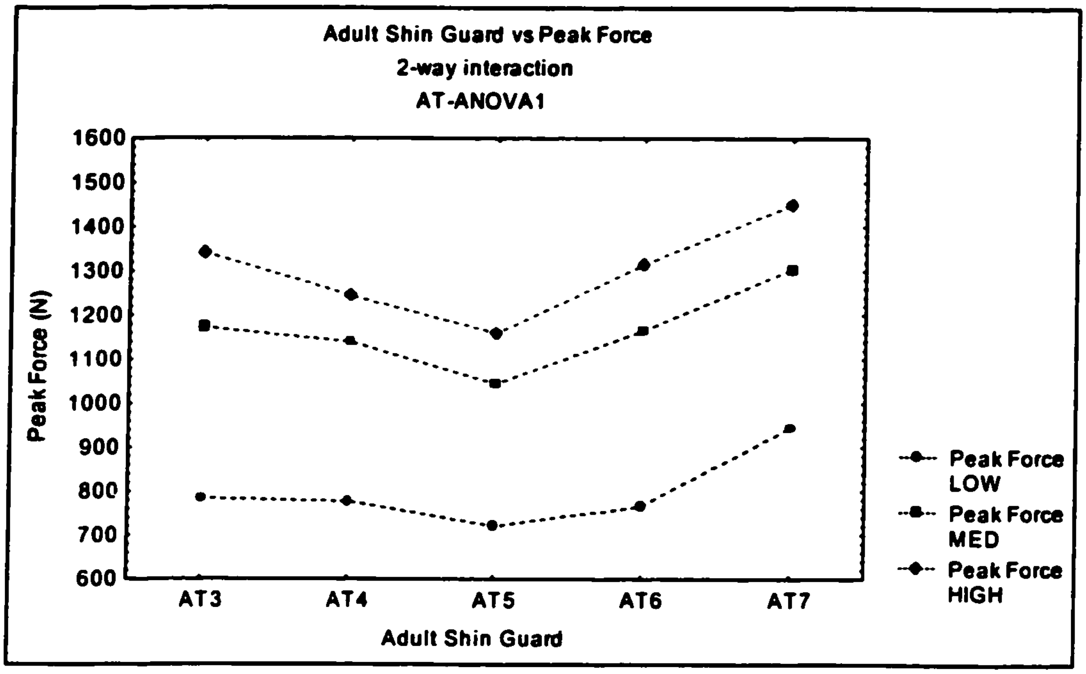
ImpactE HIGH								
19.41j	AK1		Peak	TtoPeak	LdRate	Impulse	Eabsorb	%Eabsorb
		Mean	1186.81	14.65	102190.13	17.81	13.03	67.14
		StdDev	63.79	0.29	2078.26	0.06	0.11	
		StdError	18.42	0.08	599.94	0.02	0.03	
		CoVar	5.38*	1.96	2.03	0.31	0.84	
	AK2							
		Mean	1351.59	11.99	141017.33	17.77	13.10	67.51
		StdDev	38.51	0.08	9044.95	0.05	0.10	
		StdError	11.12	0.02	2611.05	0.01	0.03	
		CoVar	2.85*	0.65	6.41	0.29	0.75	
	AK3							
		Mean	1306.05	13.13	143114.06	16.94	14.62	75.32
		StdDev	27.85	0.16	3790.50	0.14	0.24	
		StdError	8.04	0.05	1094.22	0.04	0.07	
		CoVar	2.13	1.21	2.65	0.85	1.67	
	AK4							
		Mean	1239.83	13.68	134157.74	17.04	14.46	74.48
		StdDev	23.74	0.16	3263.81	0.08	0.14	
		StdError	1.91	1.16	2.43	0.47	0.95	
		CoVar	0.55	0.33	0.70	0.13	0.27	
	AK5							
		Mean	1235.06	13.80	111268.85	17.17	14.22	73.24
		StdDev	22.25	0.32	3115.25	0.02	0.04	
		StdError	6.42	0.09	899.30	0.01	0.01	
		CoVar	1.80	2.32	2.80	0.13	0.28	
	AK6							
		Mean	1274.68	13.41	122919.00	16.77	14.91	76.80
		StdDev	14.97	0.15	2658.77	0.02	0.03	
		StdError	4.32	0.04	767.52	0.01	0.01	
		CoVar	1.17	1.10	2.16	0.12	0.22	
	AK7							
		Mean	1277.36	13.78	132720.56	17.32	13.95	71.86
		StdDev	32.84	0.07	4514.79	0.08	0.15	
		StdError	9.48	0.02	1303.31	0.02	0.04	
		CoVar	2.57*	0.50	3.40	0.48	1.09	

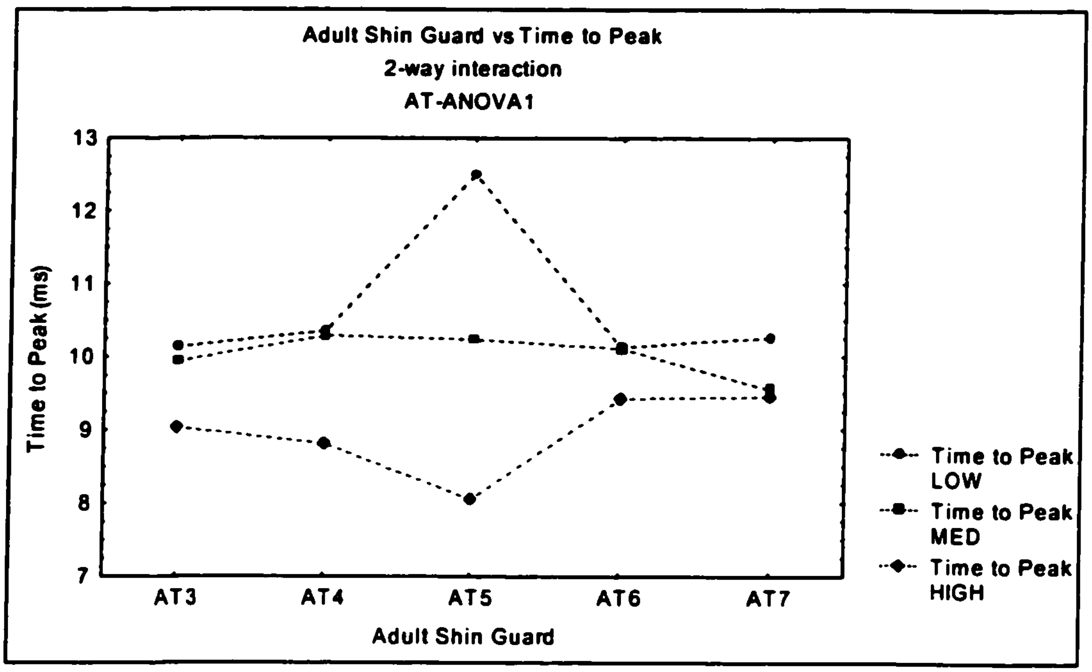
* Rejected Based on Coefficient of Variation > 2.5%

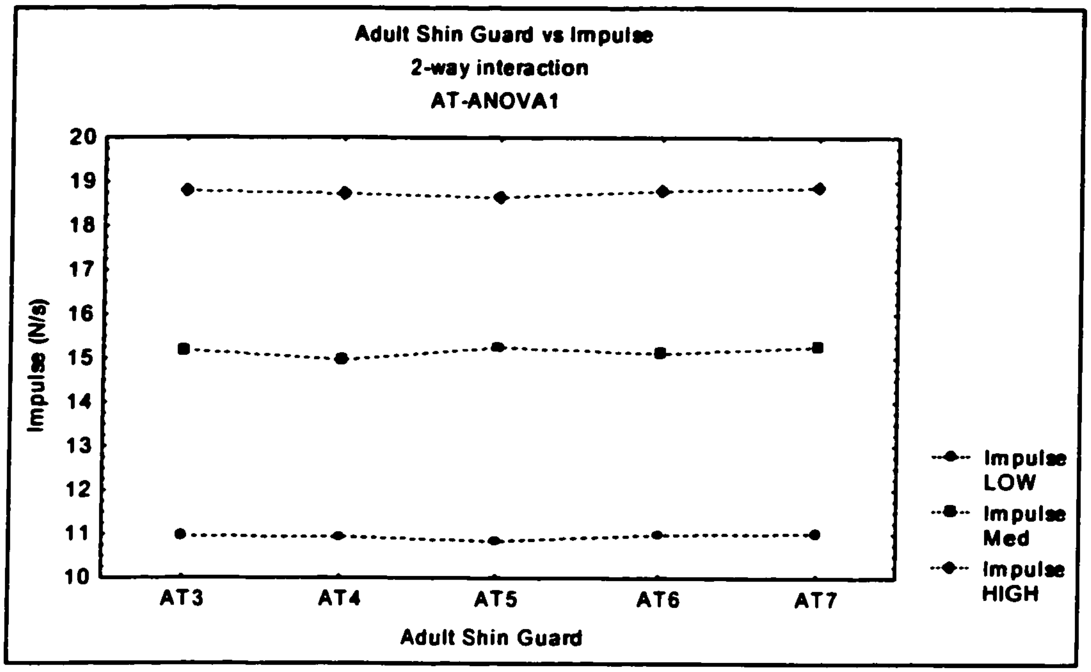
ImpactE	HIGH							
19.41j	AK8		Peak	TtoPeak	LdRate	Impulse	Eabsorb	%Eabsorb
		Mean	1394.67	13.80	107364.66	18.26	12.11	62.40
		StdDev	64.76	0.34	5930.06	0.08	0.17	
		StdError	18.69	0.10	1711.86	0.02	0.05	
		CoVar	4.64*	2.44	5.52	0.44	1.39	
	AK9							
		Mean	1510.95	12.75	129773.35	18.27	12.09	62.28
		StdDev	57.91	0.34	10426.29	0.06	0.13	
		StdError	16.72	0.10	3009.81	0.02	0.04	
		CoVar	3.83*	2.64	8.03	0.33	1.04	
	AK10							
		Mean	1289.68	14.88	90482.14	17.56	13.49	69.52
		StdDev	43.07	0.28	9374.95	0.20	0.39	
		StdError	12.43	0.08	2706.31	0.06	0.11	
		CoVar	3.34*	1.86	10.36	1.17	2.88	
	AK11							
		Mean	1222.57	14.95	82782.06	17.40	13.81	71.14
		StdDev	43.32	0.38	4349.88	0.19	0.36	
		StdError	12.51	0.11	1255.70	0.06	0.10	
		CoVar	3.54*	2.54	5.25	1.10	2.62	
	AK12							
		Mean	1712.57	11.74	179575.86	17.73	13.18	67.91
		StdDev	67.50	0.12	5801.33	0.11	0.22	
		StdError	19.49	0.03	1674.70	0.03	0.06	
		CoVar	3.94*	0.98	3.23	0.63	1.64	
	AK13							
		Mean	1720.24	11.33	159871.73	17.71	13.22	68.11
		StdDev	53.63	0.41	6609.15	0.07	0.14	
		StdError	15.48	0.12	1907.90	0.02	0.04	
		CoVar	3.12*	3.60	4.13	0.40	1.03	
	AK14							
		Mean	1705.39	10.52	179653.06	17.67	13.30	68.51
		StdDev	56.29	0.12	3860.12	0.13	0.25	
		StdError	16.25	0.03	1114.32	0.04	0.07	
		CoVar	3.30*	1.12	2.15	0.74	1.86	

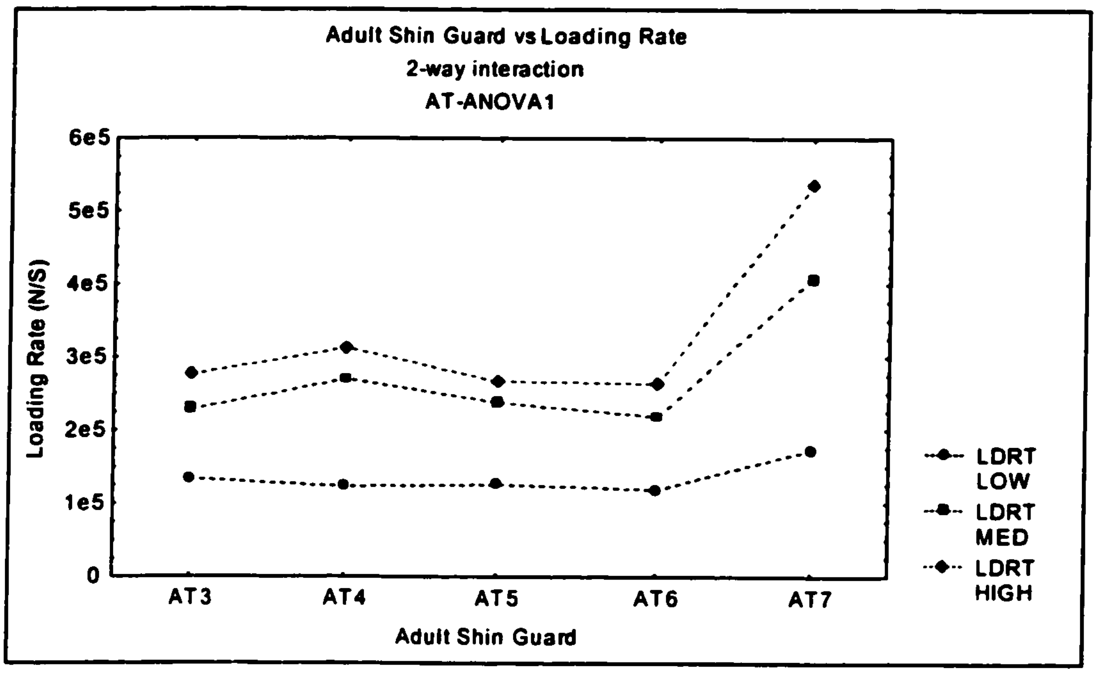
*** Rejected Based on Coefficient of Variation > 2.5%**

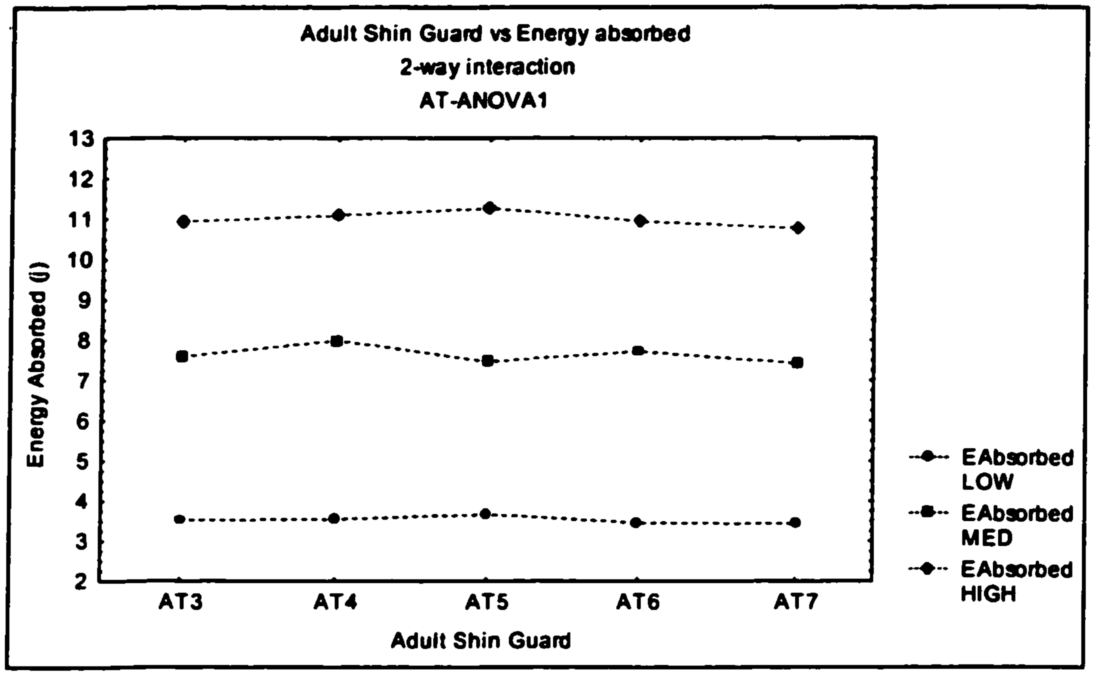
Appendix N. Interactions Effects of Adult Shin Guards Accepted for All Three Impact Energy Levels at the Tibia Location (AT-ANOVA1).



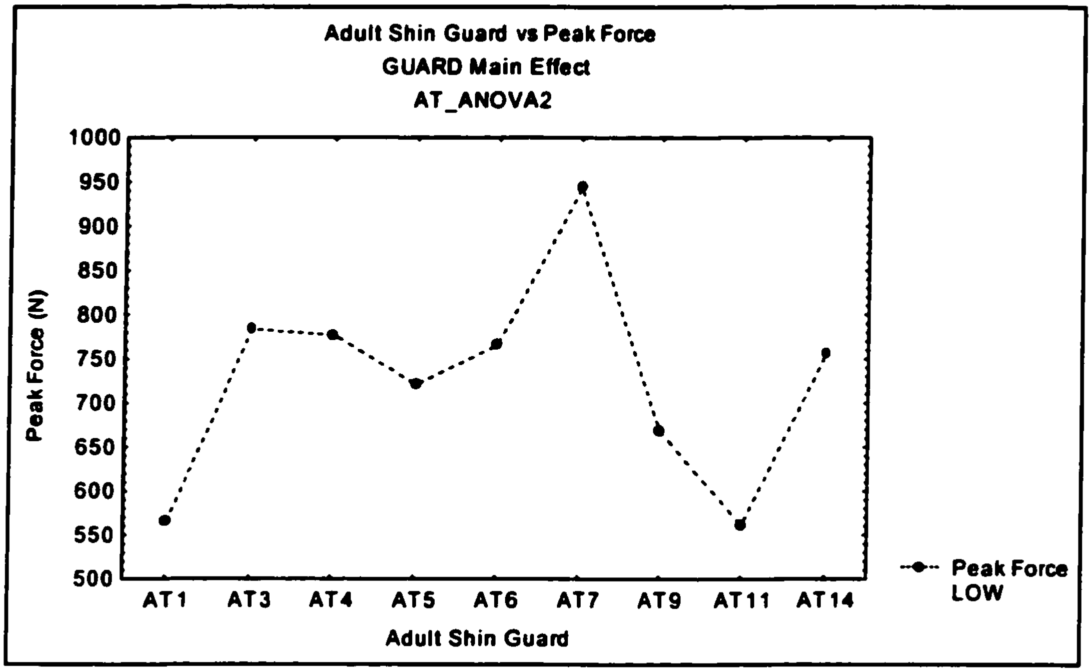


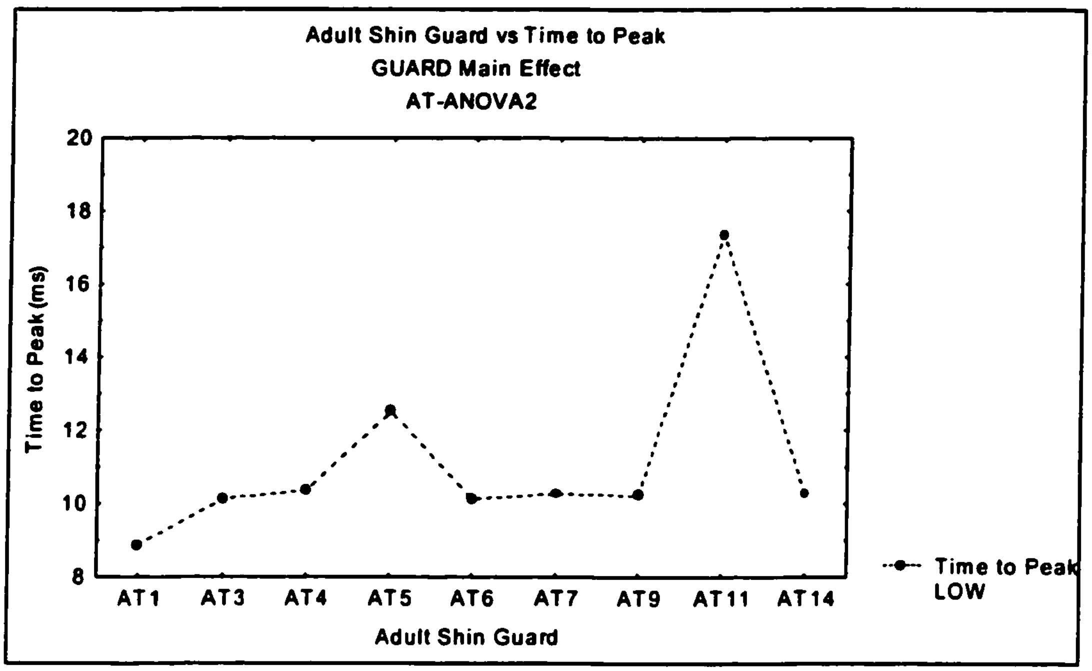

Adult Shin Guard vs Impulse
2-way interaction
AT-ANOVA1
Impulse (N/s)
20
19
18
17
16
15
14
13
12
11
10
AT3
AT4
AT5
AT6
AT7
Adult Shin Guard
Impulse LOW
Impulse Med
Impulse HIGH

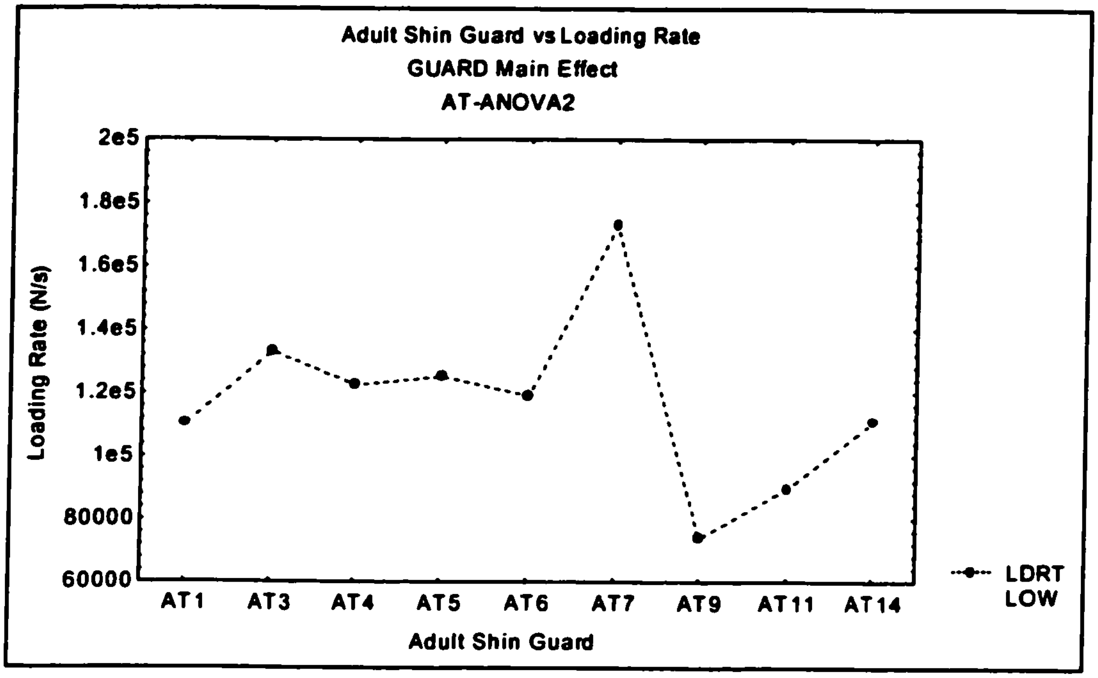

Adult Shin Guard vs Loading Rate
2-way interaction
AT-ANOVA1
Loading Rate (N/S)
6e5
5e5
4e5
3e5
2e5
1e5
0
AT3
AT4
AT5
AT6
AT7
Adult Shin Guard
LDRT LOW
LDRT MED
LDRT HIGH

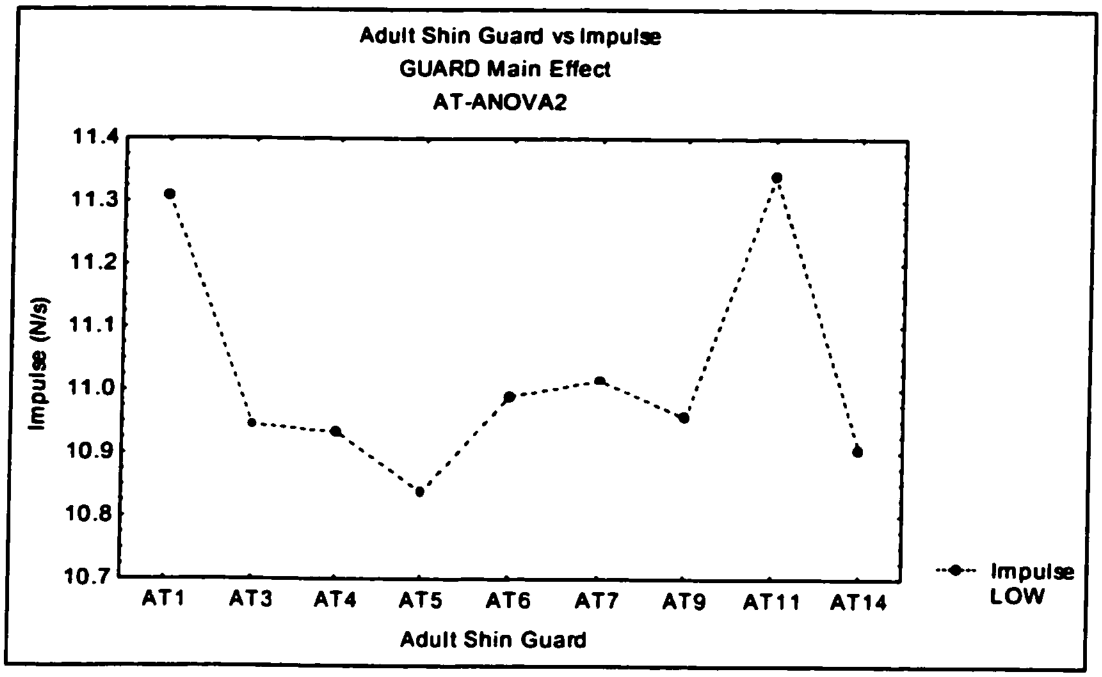

Adult Shin Guard vs Energy absorbed
2-way interaction
AT-ANOVA1
Energy Absorbed (j)
13
12
11
10
9
8
7
6
5
4
3
2
AT3
AT4
AT5
AT6
AT7
Adult Shin Guard
EAbsorbed LOW
EAbsorbed MED
EAbsorbed HIGH

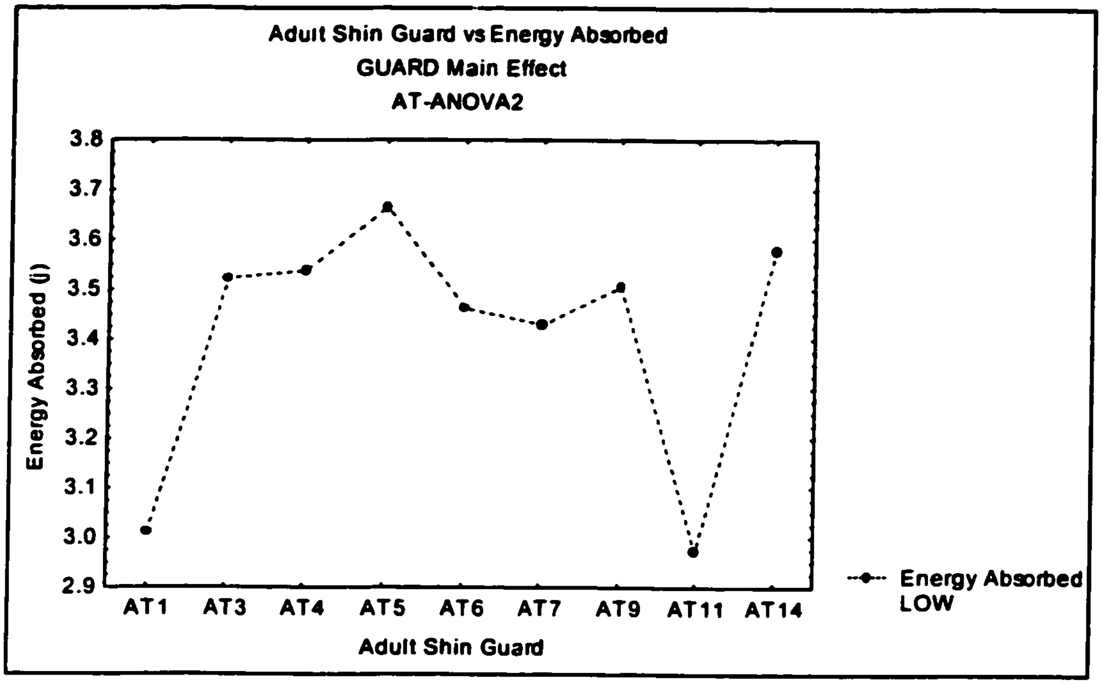
Appendix O. Main Effects of Adult Shin Guards Accepted for One Impact Energy Level at the Tibia Location (AT-ANOVA2).



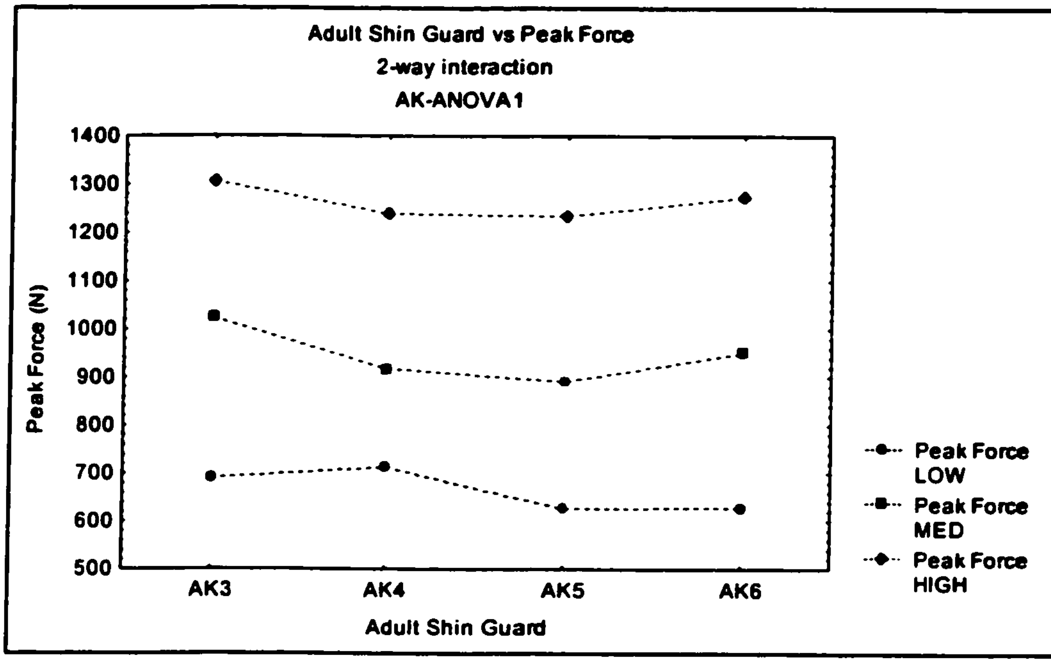


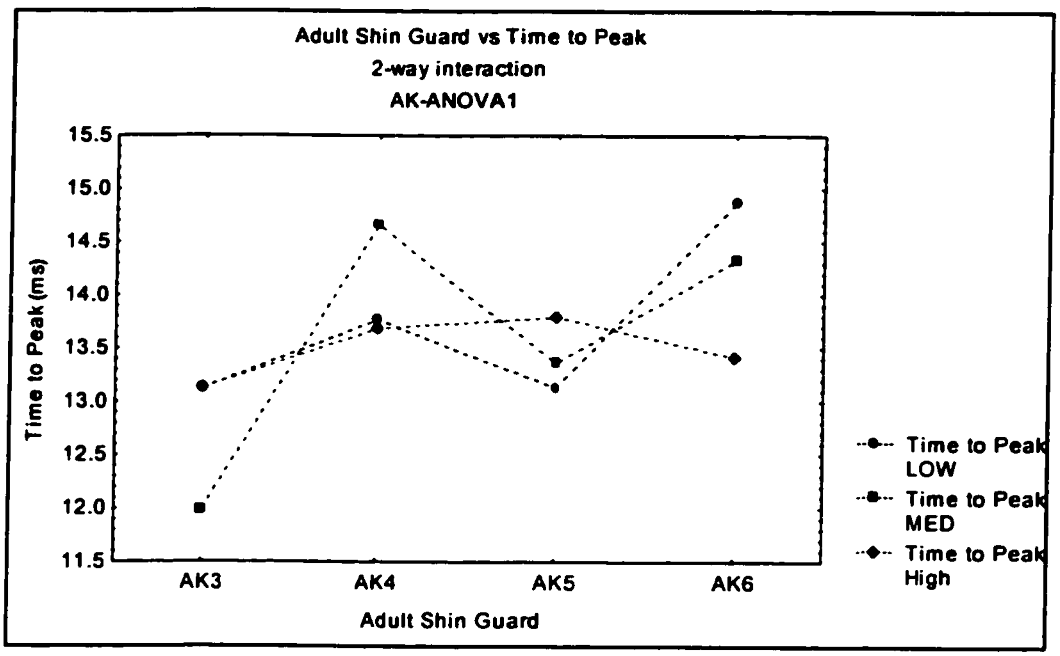

Adult Shin Guard vs Loading Rate
GUARD Main Effect
AT-ANOVA2
Loading Rate (N/s)
2e5
1.8e5
1.6e5
1.4e5
1.2e5
1e5
80000
60000
AT1
AT3
AT4
AT5
AT6
AT7
AT9
AT11
AT14
Adult Shin Guard
LDRT
LOW

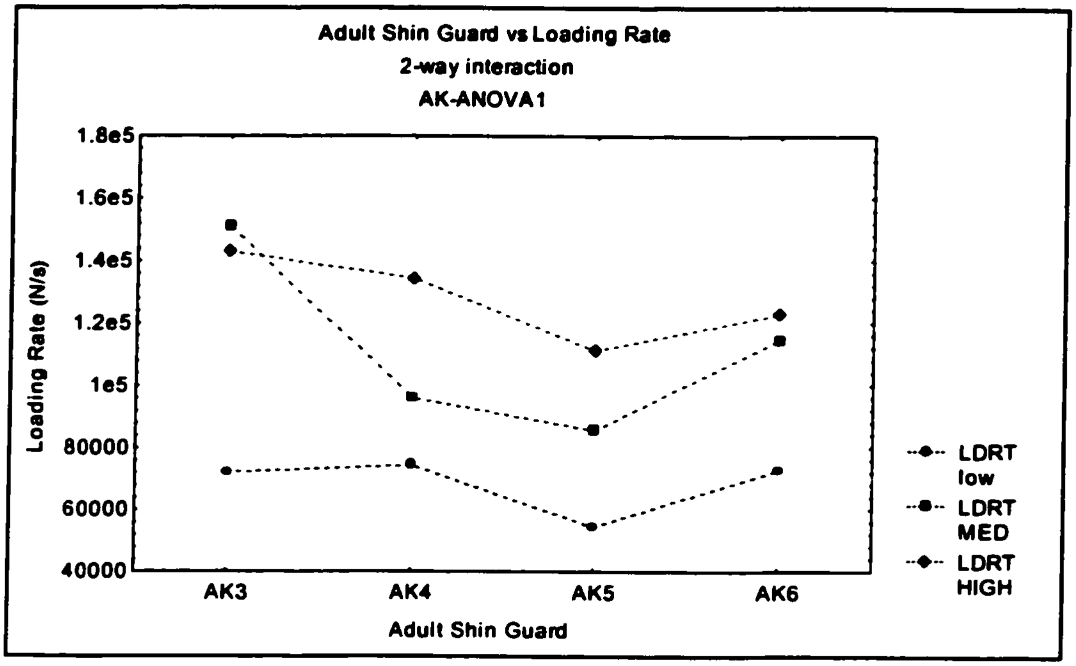

Adult Shin Guard vs Impulse
GUARD Main Effect
AT-ANOVA2
Impulse (N/s)
11.4
11.3
11.2
11.1
11.0
10.9
10.8
10.7
AT1
AT3
AT4
AT5
AT6
AT7
AT9
AT11
AT14
Adult Shin Guard
Impulse
LOW

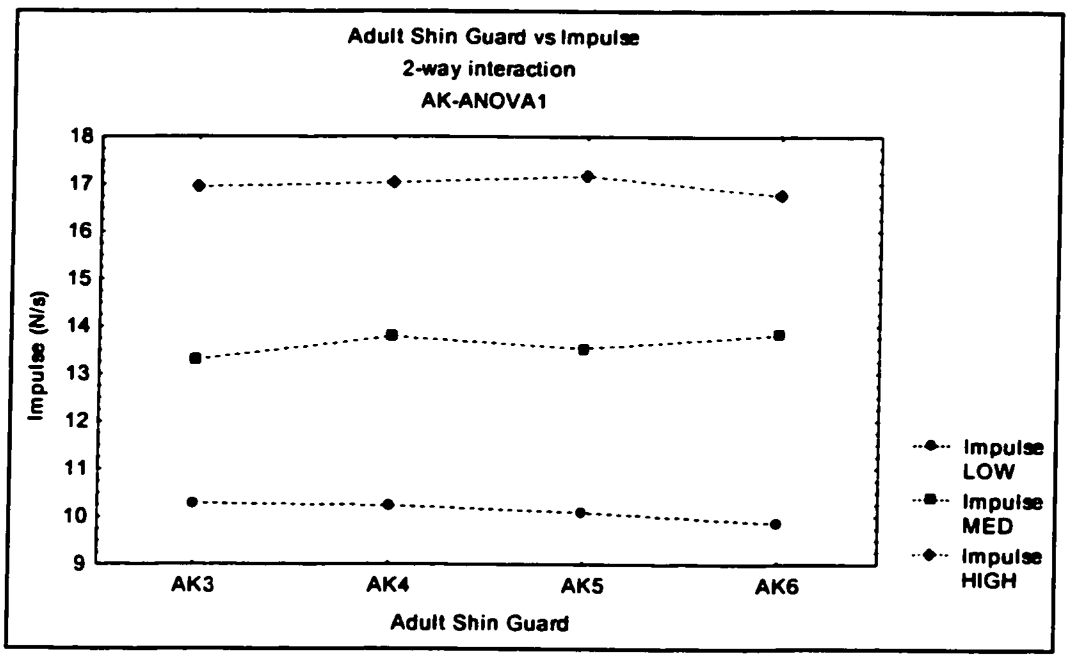

Adult Shin Guard vs Energy Absorbed
GUARD Main Effect
AT-ANOVA2
Energy Absorbed (j)
3.8
3.7
3.6
3.5
3.4
3.3
3.2
3.1
3.0
2.9
AT1
AT3
AT4
AT5
AT6
AT7
AT9
AT11
AT14
Adult Shin Guard
Energy Absorbed
LOW

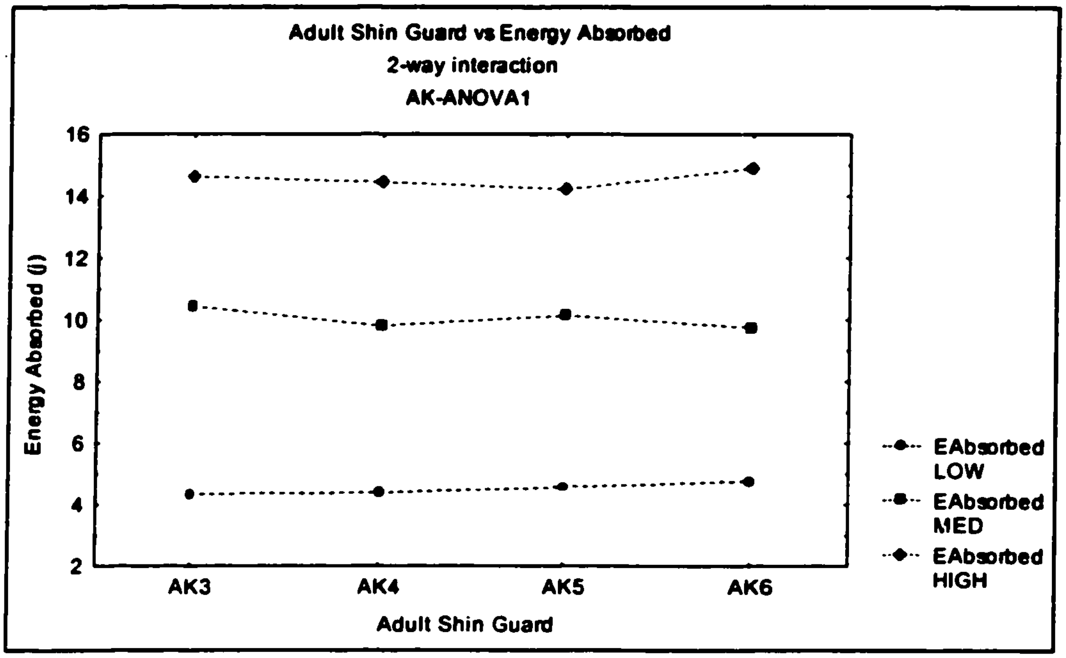
Appendix P. Interactions Effects of Adult Shin Guards Accepted for All Three Impact Energy Levels at the Knee Location (AK-ANOVA1).



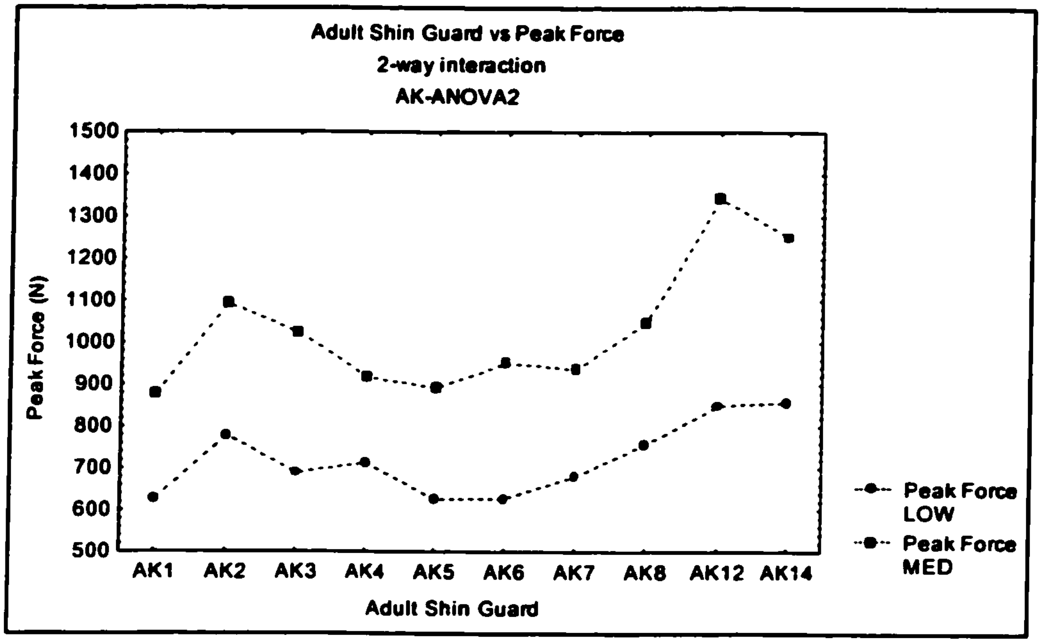


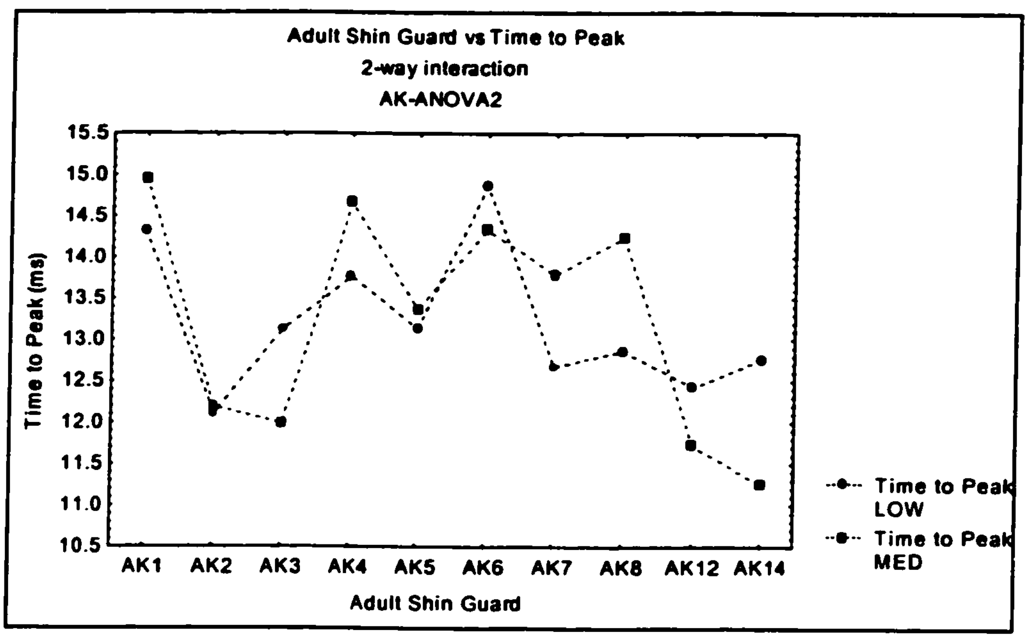

Adult Shin Guard vs Loading Rate
2-way interaction
AK-ANOVA1
Loading Rate (N/s)
1.8e5
1.6e5
1.4e5
1.2e5
1e5
80000
60000
40000
AK3
AK4
AK5
AK6
Adult Shin Guard
LDRT low
LDRT MED
LDRT HIGH

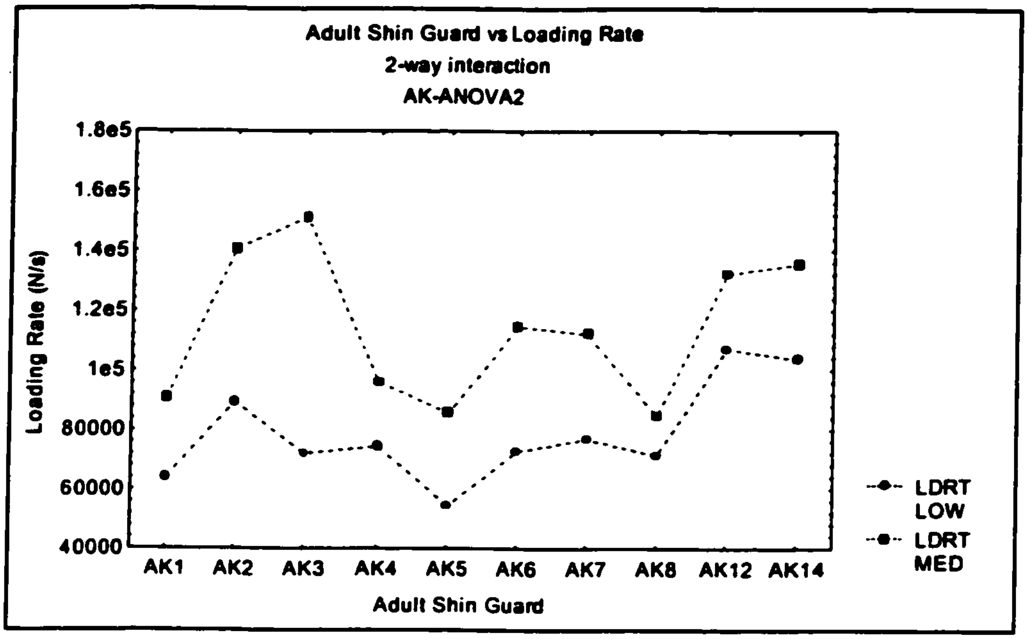

Adult Shin Guard vs Impulse
2-way interaction
AK-ANOVA1
Impulse (N/s)
18
17
16
15
14
13
12
11
10
9
AK3
AK4
AK5
AK6
Adult Shin Guard
Impulse LOW
Impulse MED
Impulse HIGH


Adult Shin Guard vs Energy Absorbed
2-way interaction
AK-ANOVA1
Energy Absorbed (J)
16
14
12
10
8
6
4
2
AK3
AK4
AK5
AK6
Adult Shin Guard
EAbsorbed LOW
EAbsorbed MED
EAbsorbed HIGH

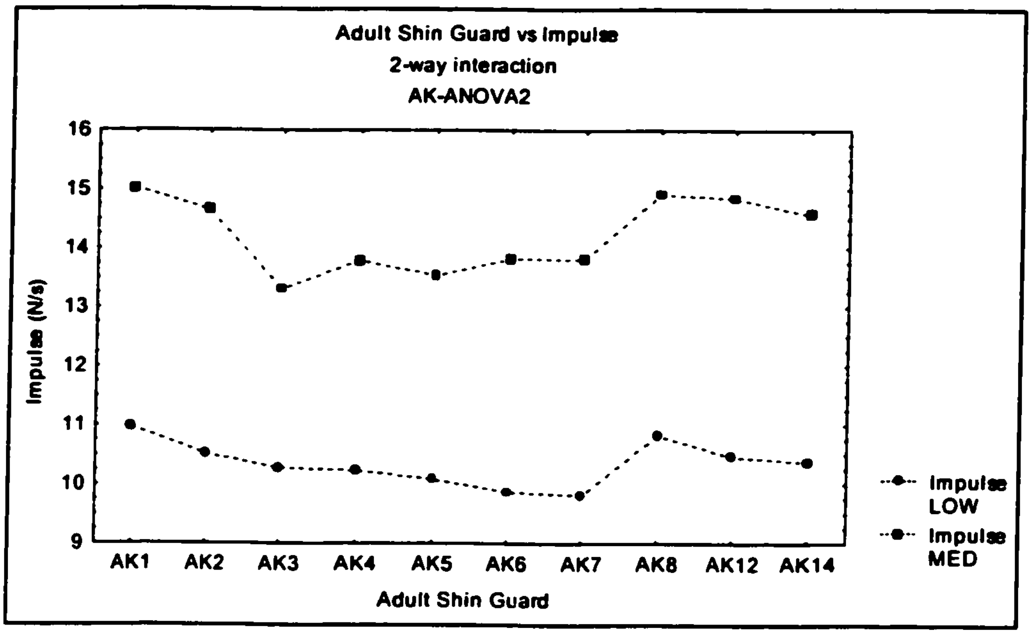
Appendix Q. Interactions Effects of Adult Shin Guards Accepted for Two Impact Energy Levels at the Knee Location (AK-ANOVA2).



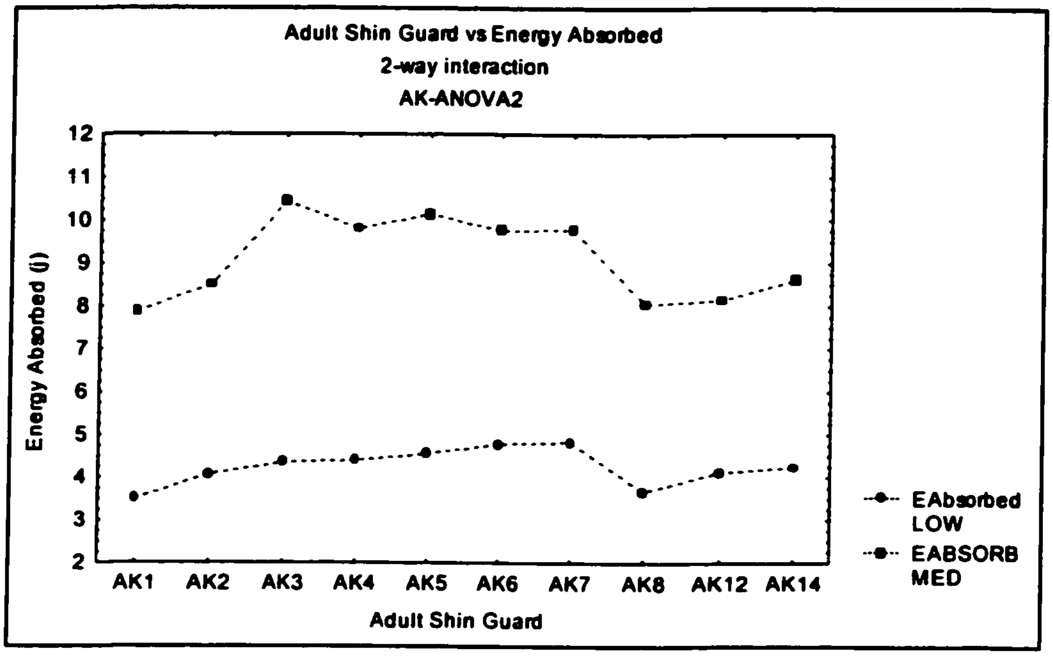




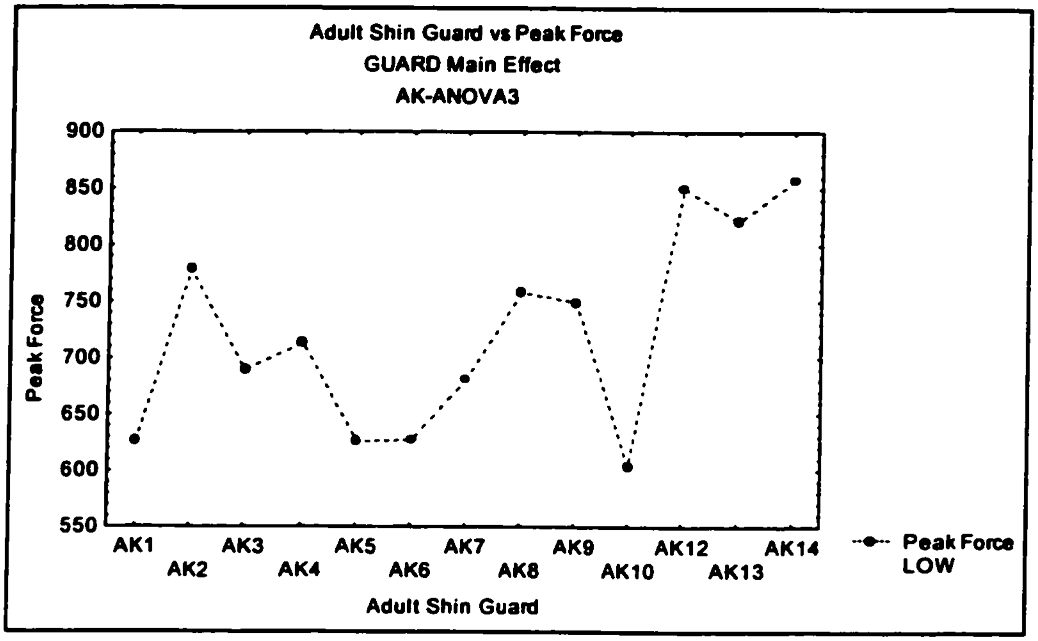
Adult Shin Guard vs Loading Rate
2-way interaction
AK-ANOVA2
1.8e5
1.6e5
1.4e5
1.2e5
1e5
80000
60000
40000
Loading Rate (N/s)
AK1 AK2 AK3 AK4 AK5 AK6 AK7 AK8 AK12 AK14
Adult Shin Guard
LDRT LOW
LDRT MED

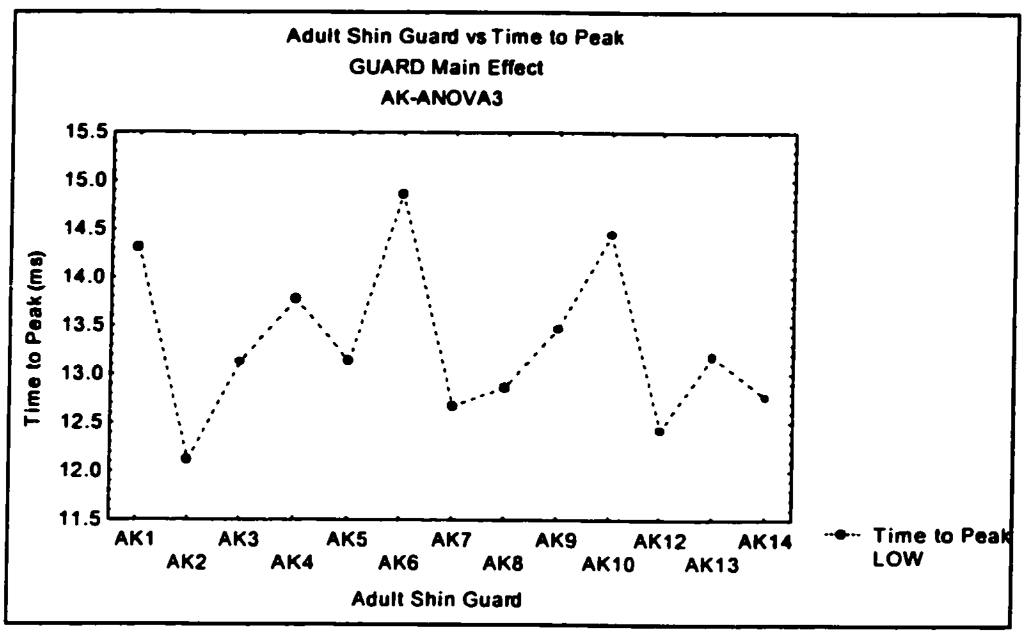


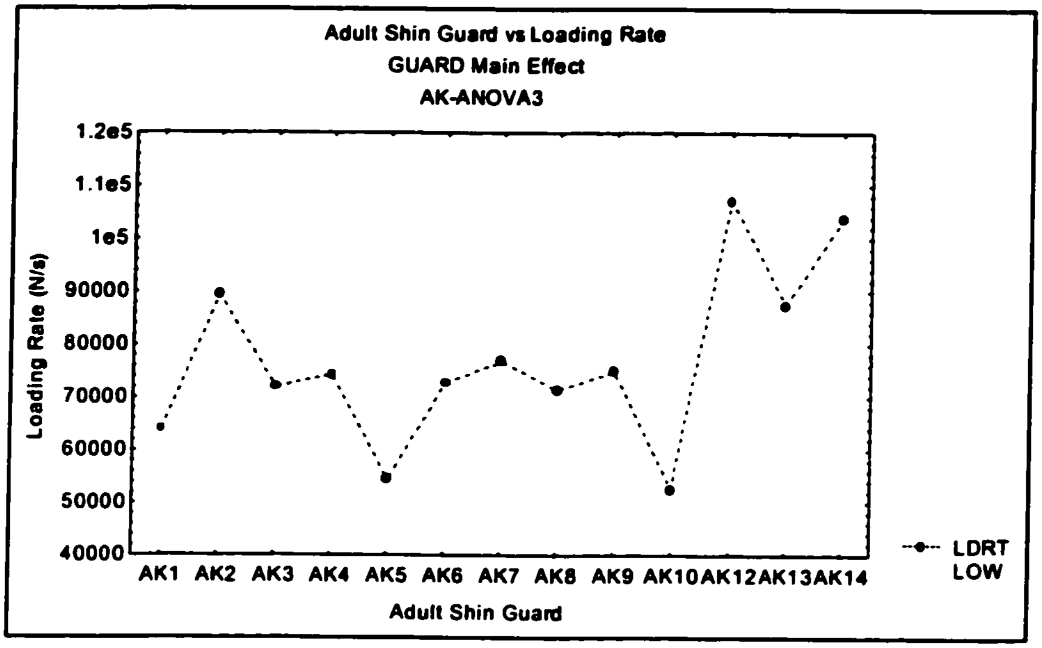
Adult Shin Guard vs Impulse
2-way interaction
AK-ANOVA2
16
15
14
13
12
11
10
9
Impulse (N/s)
AK1 AK2 AK3 AK4 AK5 AK6 AK7 AK8 AK12 AK14
Adult Shin Guard
Impulse LOW
Impulse MED

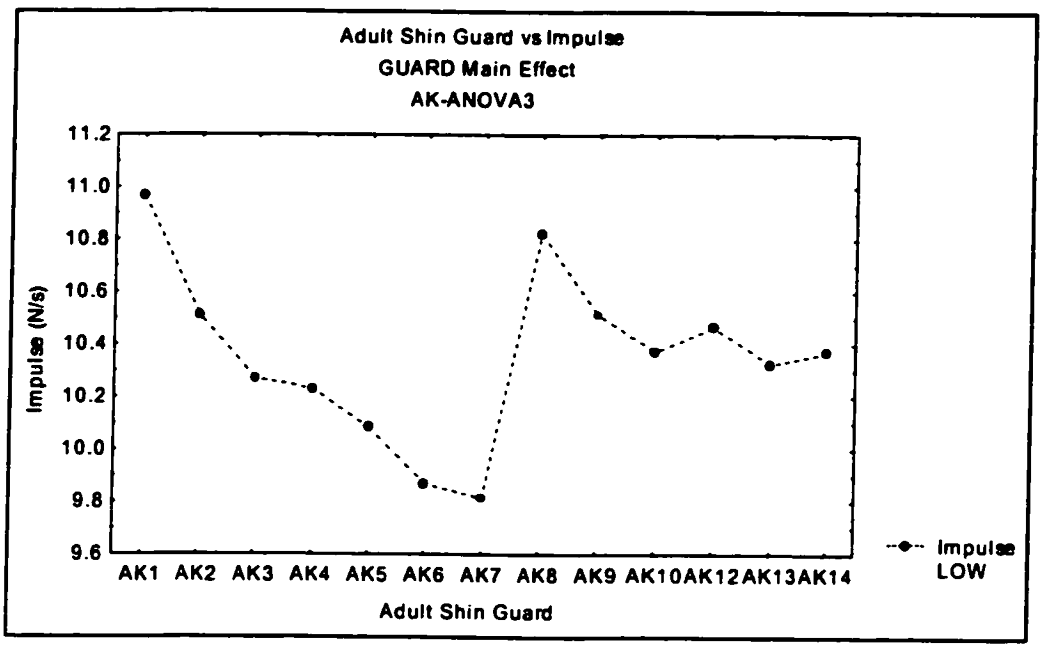

Adult Shin Guard vs Energy Absorbed
2-way interaction
AK-ANOVA2
Energy Absorbed (J)
12
11
10
9
8
7
6
5
4
3
2
AK1
AK2
AK3
AK4
AK5
AK6
AK7
AK8
AK12
AK14
Adult Shin Guard
EAbsorbed LOW
EABSORB MED

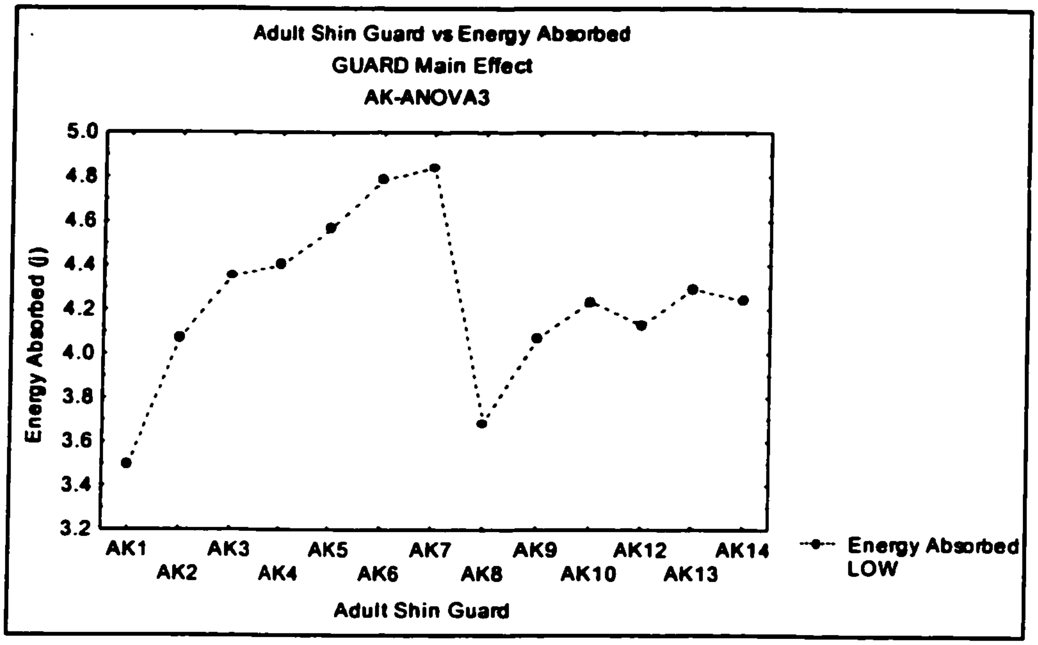
Appendix R. Main Effects of Adult Shin Guards Accepted for One Impact Energy Levels at the Knee Location (AK-ANOVA 3).






Adult Shin Guard vs Loading Rate
GUARD Main Effect
AK-ANOVA3
Loading Rate (N/s)
1.2e5
1.1e5
1e5
90000
80000
70000
60000
50000
40000
AK1 AK2 AK3 AK4 AK5 AK6 AK7 AK8 AK9 AK10 AK12 AK13 AK14
Adult Shin Guard
LDRT
LOW


Adult Shin Guard vs Impulse
GUARD Main Effect
AK-ANOVA3
Impulse (N/s)
11.2
11.0
10.8
10.6
10.4
10.2
10.0
9.8
9.6
AK1 AK2 AK3 AK4 AK5 AK6 AK7 AK8 AK9 AK10 AK12 AK13 AK14
Adult Shin Guard
Impulse
LOW


Adult Shin Guard vs Energy Absorbed
GUARD Main Effect
AK-ANOVA3
Energy Absorbed (J)
5.0
4.8
4.6
4.4
4.2
4.0
3.8
3.6
3.4
3.2
AK1
AK2
AK3
AK4
AK5
AK6
AK7
AK8
AK9
AK10
AK12
AK13
AK14
Adult Shin Guard
Energy Absorbed
LOW

Appendix S. Summary of Significant Comparisons in the Post Hoc Analyses for the AT-ANOVA1 Analyses of Variance.

Peak Force

Means (at-anova1.sta)
$F(8,110)=87.41$; $p<0.000$

	Depend. Fp	A3	A4	A5	A6	A7	
AL3	783.17		NS	S	S	S	
AL4	777.34			S	S	S	
AL5	720.44				S	S	
AL6	765.52					S	
AL7	944.00						9
AM3	1172.13		S	S	NS	S	
AM4	1139.76			S	S	S	
AM5	1044.45				S	S	
AM6	1165.61					S	
AM7	1303.75						9
AH3	1340.24		S	S	S	S	
AH4	1243.72			S	S	S	
AH5	1158.83				S	S	
AH6	1315.22					S	
AH7	1449.60						10
Total							28

Time to Peak

Means (at-anova1.sta)
$F(8,110)=92.65$; $p<0.000$

	Depend. TtoP	A3	A4	A5	A6	A7	
AL3	10.13		S	S	NS	S	
AL4	10.36			S	S	NS	
AL5	12.50				S	S	
AL6	10.13					S	
AL7	10.27						8
AM3	9.94		S	S	S	S	
AM4	10.28			NS	S	S	
AM5	10.24				S	S	
AM6	10.11					S	
AM7	9.55						9
AH3	9.03		S	S	S	S	
AH4	8.81			S	S	S	
AH5	8.05				S	S	
AH6	9.43					NS	
AH7	9.46						9
Total							26

S= Significant Comparison
NS=Non Significant Comparison

Loading Rate

Means (at-anova1.sta) $F(8,110)=517.11$; $p<0.000$	Depend. LR	A3	A4	A5	A6	A7	
AL3	132961		S	NS	S	S	
AL4	122470			NS	NS	S	
AL5	125172				NS	S	
AL6	119132					S	
AL7	172932						6
AM3	228283		S	S	S	S	
AM4	269209			S	S	S	
AM5	237882				S	S	
AM6	218823					S	
AM7	407784						10
AH3	276481		S	S	S	S	
AH4	311981			S	S	S	
AH5	266676				NS	S	
AH6	264264					S	
AH7	536564						9
Total							25

Impulse

Means (at-anova1.sta) $F(8,110)=9.96$; $p<.0000$	Depend. I	A3	A4	A5	A6	A7	
AL3	10.9444		NS	S	NS	NS	
AL4	10.9325			NS	NS	NS	
AL5	10.8379				S	S	
AL6	10.9896					NS	
AL7	11.0144						3
AM3	15.1824		S	NS	NS	NS	
AM4	14.9574			S	S	S	
AM5	15.2534				S	NS	
AM6	15.1064					S	
AM7	15.2708						6
AH3	18.7982		NS	S	NS	NS	
AH4	18.7288			NS	NS	S	
AH5	18.6497				S	S	
AH6	18.793					NS	
AH7	18.8687						4
Total							13

S= Significant Comparison

NS=Non Significant Comparison

Energy Absorbed

Means (at-anova1.sta)
***F* (8,110)=9.40; *p* <.0000**

	Depend. EA	A3	A4	A5	A6	A7	
AL3	3.52249		NS	NS	NS	NS	
AL4	3.5384			NS	NS	NS	
AL5	3.66312				NS	S	
AL6	3.46183					NS	
AL7	3.42833						1
AM3	7.58881		S	NS	NS	NS	
AM4	7.98588			S	S	S	
AM5	7.45867				S	NS	
AM6	7.72511					S	
AM7	7.41752						6
AH3	10.9336		NS	S	NS	NS	
AH4	11.0889			NS	NS	S	
AH5	11.2657				S	S	
AH6	10.945					NS	
AH7	10.7728						4
							11

S= Significant Comparison
NS=Non Significant Comparison

Appendix T. Summary of Significant Comparisons in the Post Hoc Analyses for the AT-ANOVA2 Analyses of Variance.

Peak Force

Means (at-anova2.sta)
***F*(8,99)=3349.98; *p* <0.000**

	Fp	AL1	AL3	AL4	AK5	AL6	AL7	AL9	AL11	AL14	
AL1	565.17		S	S	S	S	S	S	NS	S	
AL3	783.17			NS	S	S	S	S	S	S	
AL4	777.34				S	S	S	S	S	S	
AK5	720.44					S	S	S	S	S	
AL6	765.52						S	S	S	S	
AL7	944.00							S	S	S	
AL9	667.87								S	S	
AL11	561.33									S	
AL14	755.88										
Total											34

Time to Peak

Means (at-anova2.sta)
***F*(8,99)=79.44; *p* <0.000**

	TtoP	AL1	AL3	AL4	AK5	AL6	AL7	AL9	AL11	AL14	
AL1	8.87		NS	S	S	NS	S	S	S	S	
AL3	10.13			NS	S	NS	NS	NS	S	NS	
AL4	10.36				S	NS	NS	NS	S	NS	
AK5	12.50					S	S	S	S	S	
AL6	10.13						NS	NS	S	NS	
AL7	10.27							NS	S	NS	
AL9	10.22								S	NS	
AL11	17.35									S	
AL14	10.26										
Total											21

S= Significant Comparison

NS=Non Significant Comparison

Loading Rate

Means (at-anova2.sta)
***F* (8,99)=332.23; *p* <0.000**

	LR	AL1	AL3	AL4	AK5	AL6	AL7	AL9	AL11	AL14	
AL1	110214.84		S	S	S	S	S	S	S	NS	
AL3	132961.05			S	S	S	S	S	S	S	
AL4	122470.20				NS	NS	S	S	S	S	
AK5	125172.18					NS	S	S	S	S	
AL6	119132.20						S	S	S	S	
AL7	172932.28							S	S	S	
AL9	73877.25								S	S	
AL11	89486.79									S	
AL14	110984.97										
Total											32

Impulse

Means (at-anova2.sta)
***F* (8,99)=59.86; *p* <0.000**

	I	AL1	AL3	AL4	AK5	AL6	AL7	AL9	AL11	AL14	
AL1	11.31		S	S	S	S	S	S	NS	S	
AL3	10.94			NS	S	NS	NS	NS	S	NS	
AL4	10.93				NS	NS	NS	NS	S	NS	
AK5	10.84					S	S	S	S	NS	
AL6	10.99						NS	NS	S	NS	
AL7	11.01							NS	S	S	
AL9	10.96								S	NS	
AL11	11.34									S	
AL14	10.90										
Total											19

S= Significant Comparison
NS=Non Significant Comparison

Energy Absorbed

Means (at-anova2.sta) $F(8,99)=61.12$; $p<0.000$	EA	AL1	AL3	AL4	AK5	AL6	AL7	AL9	AL11	AL14	
AL1	3.01		S	S	S	S	S	S	NS	S	
AL3	3.52			NS	NS	NS	NS	NS	S	NS	
AL4	3.54				NS	NS	NS	NS	S	NS	
AK5	3.66					S	S	S	S	NS	
AL6	3.46						NS	NS	S	NS	
AL7	3.43							NS	S	S	
AL9	3.51								S	NS	
AL11	2.97									S	
AL14	3.58										
Total											18

S= Significant Comparison

NS=Non Significant Comparison

Appendix U. Summary of Significant Comparisons in the Post Hoc Analyses for the AK-ANOVA1 Analyses of Variance.

Peak Force

Means (ak-anova1.sta) $F(6,88)=90.61$; $p<0.000$	Depend. Fp	A3	A4	A5	A6	
AL3	689.20		S	S	S	
AL4	712.96			S	S	
AL5	625.88				NS	
AL6	627.27					5
AM3	1023.14		S	S	S	
AM4	916.86			S	S	
AM5	891.56				S	
AM6	950.89					6
AH3	1306.05		S	S	S	
AH4	1239.83			NS	S	
AH5	1235.06				S	
AH6	1274.68					5
Total						16

Time to Peak

Means (ak-anova1.sta) $F(6,88)=76.39$; $p<0.000$	Depend. Tp	A3	A4	A5	A6	
AL3	13.13		S	NS	S	
AL4	13.77			S	S	
AL5	13.13				S	
AL6	14.87					5
AM3	11.99		S	S	S	
AM4	14.66			S	S	
AM5	13.36				S	
AM6	14.33					6
AH3	13.13		S	S	NS	
AH4	13.68			NS	NS	
AH5	13.80				S	
AH6	13.41					3
Total						14

S= Significant Comparison
NS=Non Significant Comparison

Loading Rate

Means (ak-anova1.sta)
F (6,88)=120.10; *p* <0.000

	Depend. LR	A3	A4	A5	A6	
AL3	71985.07		NS	S	NS	
AL4	74322.96			S	NS	
AL5	54401.46				S	
AL6	72740.65					3
AM3	151101.63		S	S	S	
AM4	95986.48			S	S	
AM5	85502.57				S	
AM6	114588.55					6
AH3	143114.06		S	S	S	
AH4	134157.73			S	S	
AH5	111268.84				S	
AH6	122918.99					6
Total						15

Impulse

Means (ak-anova1.sta)
F (6,88)=61.65; *p* <.0000

	Depend. I	A3	A4	A5	A6	
AL3	10.27		NS	S	S	
AL4	10.23			S	S	
AL5	10.08				S	
AL6	9.87					5
AM3	13.30		S	S	S	
AM4	13.79			S	NS	
AM5	13.53				S	
AM6	13.82					5
AH3	16.94		NS	S	S	
AH4	17.04			S	S	
AH5	17.17				S	
AH6	16.77					5
Total						15

S= Significant Comparison
NS=Non Significant Comparison

Energy Absorbed

Means (ak-anova1.sta) $F(6,88)=63.40$; $p<.0000$	Depend. EA	A3	A4	A5	A6	
AL3	4.35		NS	NS	NS	
AL4	4.40			NS	NS	
AL5	4.56				NS	
AL6	4.78					0
AM3	10.44		S	NS	S	
AM4	9.81			NS	NS	
AM5	10.15				NS	
AM6	9.76					2
AH3	14.62		NS	NS	NS	
AH4	14.46			NS	S	
AH5	14.22				S	
AH6	14.91					2
Total						4

S= Significant Comparison

NS=Non Significant Comparison

Appendix V. Summary of Significant Comparisons in the Post Hoc Analyses for the AK-ANOVA2 Analyses of Variance.

Peak Force

Means (ak-anova2.sta)
$F(9,110)=299.37$; $p<0.000$

	Depend. Fp	A1	A12	A14	A2	A3	A4	A5	A6	A7	A8	
L1	625.73		S	S	S	S	S	NS	NS	S	S	
L12	850.26			NS	S	S	S	S	S	S	S	
L14	857.59				S	S	S	S	S	S	S	
L2	778.34					S	S	S	S	S	S	
L3	689.20						S	S	S	NS	S	
L4	712.96							S	S	S	S	
L5	625.88								NS	S	S	
L6	627.27									S	S	
L7	680.90										S	
L8	757.90											40
M1	877.14		S	S	S	S	S	NS	S	S	S	
M12	1342.30			S	S	S	S	S	S	S	S	
M14	1250.71				S	S	S	S	S	S	S	
M2	1093.24					S	S	S	S	S	S	
M3	1023.14						S	S	S	S	S	
M4	916.86							S	S	S	S	
M5	891.56								S	S	S	
M6	950.89									NS	S	
M7	935.85										S	
M8	1049.91											43
Total												83

Time to Peak

Means (ak-anova2.sta)
$F(9,110)=33.62$; $p<.0000$

	Depend. Tp	A1	A12	A14	A2	A3	A4	A5	A6	A7	A8	
L1	14.31		S	S	S	S	NS	S	NS	S	S	
L12	12.42			NS	NS	S	S	S	S	NS	NS	
L14	12.76				S	NS	S	NS	S	NS	NS	
L2	12.11					S	S	S	S	S	S	
L3	13.13						S	NS	S	NS	NS	
L4	13.77							S	S	S	S	
L5	13.13								S	NS	NS	
L6	14.87									S	S	
L7	12.67										NS	
L8	12.87											29
M1	14.95		S	S	S	S	NS	S	S	S	S	
M12	11.72			NS	NS	NS	S	S	S	S	S	
M14	11.25				S	S	S	S	S	S	S	
M2	12.19					NS	S	S	S	S	S	
M3	11.99						S	S	S	S	S	
M4	14.66							S	NS	S	NS	
M5	13.36								S	NS	S	
M6	14.33									NS	NS	
M7	13.79										NS	
M8	14.25											34
Total												63

S= Significant Comparison
NS=Non Significant Comparison

Loading Rate

Means (ak-anova2.sta)
$F(9,110)=100.68$; $p<0.000$

	Depend. LR	A1	A12	A14	A2	A3	A4	A5	A6	A7	A8	
L1	63982.70		S	S	S	S	S	S	S	S	S	
L12	107162.97			NS	S	S	S	S	S	S	S	
L14	103895.95				S	S	S	S	S	S	S	
L2	89418.80					S	S	S	S	S	S	
L3	71985.07						NS	S	NS	NS	NS	
L4	74322.96							S	NS	NS	NS	
L5	54401.46								S	S	S	
L6	72740.65									NS	NS	
L7	76906.88										NS	
L8	71436.13											34
M1	90484.02		S	S	S	S	NS	NS	S	S	NS	
M12	132388.20			NS	S	S	S	S	S	S	S	
M14	135668.05				NS	S	S	S	S	S	S	
M2	140884.77					S	S	S	S	S	S	
M3	151101.63						S	S	S	S	S	
M4	95986.48							S	S	S	S	
M5	85502.57								S	S	NS	
M6	114588.55									NS	S	
M7	112079.02										S	
M8	84590.25											38
Total												72

Impulse

Means (ak-anova2.sta)
$F(9,110)=141.80$; $p<0.000$

	Depend. I	A1	A12	A14	A2	A3	A4	A5	A6	A7	A8	
L1	10.96		S	S	S	S	S	S	S	S	S	
L12	10.46			NS	NS	S	S	S	S	S	S	
L14	10.37				S	NS	S	S	S	S	S	
L2	10.51					S	S	S	S	S	S	
L3	10.27						NS	S	S	S	S	
L4	10.23							S	S	S	S	
L5	10.08								S	S	S	
L6	9.87									NS	S	
L7	9.81										S	
L8	10.82											40
M1	15.02		S	S	S	S	S	S	S	S	NS	
M12	14.86			S	S	S	S	S	S	S	NS	
M14	14.58				NS	S	S	S	S	S	S	
M2	14.65					S	S	S	S	S	S	
M3	13.30						S	S	S	S	S	
M4	13.79							S	NS	NS	S	
M5	13.53								S	S	S	
M6	13.82									NS	S	
M7	13.81										S	
M8	14.92											39
Total												79

S= Significant Comparison
NS=Non Significant Comparison

Energy Absorbed

Means (ak-anova2.sta)
$F(9,110)=212.32$; $p<0.000$

	Depend. EA	A1	A12	A14	A2	A3	A4	A5	A6	A7	A8	
L1	3.49		S	S	S	S	S	S	S	S	S	
L12	4.13			NS	NS	S	S	S	S	S	S	
L14	4.24				S	NS	S	S	S	S	S	
L2	4.07					S	S	S	S	S	S	
L3	4.35						NS	S	S	S	S	
L4	4.40							S	S	S	S	
L5	4.56								S	S	S	
L6	4.78									NS	S	
L7	4.84										S	
L8	3.68											40
M1	7.88		S	S	S	S	S	S	S	S	S	
M12	8.16			S	S	S	S	S	S	S	NS	
M14	8.62				NS	S	S	S	S	S	S	
M2	8.51					S	S	S	S	S	S	
M3	10.44						S	S	S	S	S	
M4	9.81							S	NS	NS	S	
M5	10.15								S	S	S	
M6	9.76									NS	S	
M7	9.78										S	
M8	8.05											40
Total												80

S= Significant Comparison
NS=Non Significant Comparison

Appendix W. Summary of Significant Comparisons in the Post Hoc Analyses for the AK-ANOVA3 Analyses of Variance.

Peak Force

Means (ak-anova3.sta)
$F(12,143)=912.97$; $p<0.000$

	Fp	AL1	AL2	AL3	AL4	AL5	AL6	AL7	AL8	AL9	AL10	AL12	AL13	AL14	
AL1	625.73		S	S	S	NS	NS	S	S	S	S	S	S	S	
AL2	778.34			S	S	S	S	S	S	S	S	S	S	S	
AL3	689.20				S	S	S	NS	S	S	S	S	S	S	
AL4	712.96					S	S	S	S	S	S	S	S	S	
AL5	625.88						NS	S	S	S	S	S	S	S	
AL6	627.27							S	S	S	S	S	S	S	
AL7	680.90								S	S	S	S	S	S	
AL8	757.90									NS	S	S	S	S	
AL9	749.63										S	S	S	S	
AL10	604.10											S	S	S	
AL12	850.26												S	NS	
AL13	821.40													S	
AL14	857.59														
Total															72

Time to Peak

Means (ak-anova3.sta)
$F(12,143)=34.80$; $p<0.000$

	Tp	AL1	AL2	AL3	AL4	AL5	AL6	AL7	AL8	AL9	AL10	AL12	AL13	AL14	
AL1	14.31		S	S	NS	S	NS	S	S	S	NS	S	S	S	
AL2	12.11			S	S	S	S	NS	S	S	S	NS	S	NS	
AL3	13.13				NS	NS	S	NS	NS	NS	S	S	NS	NS	
AL4	13.77					NS	S	S	S	NS	S	S	NS	S	
AL5	13.13						S	NS	NS	NS	S	S	NS	NS	
AL6	14.87							S	S	S	NS	S	S	S	
AL7	12.67								NS	S	S	NS	NS	NS	
AL8	12.87									NS	S	NS	NS	NS	
AL9	13.47										S	S	NS	S	
AL10	14.44											S	S	S	
AL12	12.42												S	NS	
AL13	13.19													NS	
AL14	12.76														
Total															45

S= Significant Comparison
NS=Non Significant Comparison

Loading Rate

Means (ak-anova3.sta) $F(12,143)=275.66$; $p<0.000$	LR	AL1	AL2	AL3	AL4	AL5	AL6	AL7	AL8	AL9	AL10	AL12	AL13	AL14	
AL1	63982.70		S	S	S	S	S	S	S	S	S	S	S	S	
AL2	89418.80			S	S	S	S	S	S	S	S	S	S	S	
AL3	71985.07				NS	S	NS	S	NS	NS	S	S	S	S	
AL4	74322.96					S	NS	NS	NS	NS	S	S	S	S	
AL5	54401.46						S	S	S	S	NS	S	S	S	
AL6	72740.65							NS	NS	NS	S	S	S	S	
AL7	76906.88								S	NS	S	S	S	S	
AL8	71436.13									NS	S	S	S	S	
AL9	74897.89										S	S	S	S	
AL10	52579.03											S	S	S	
AL12	107162.97												S	NS	
AL13	87503.38													S	
AL14	103895.95														
Total															63

Impulse

Means (ak-anova3.sta) $F(12,143)=195.71$; $p<0.000$	I	AL1	AL2	AL3	AL4	AL5	AL6	AL7	AL8	AL9	AL10	AL12	AL13	AL14	
AL1	10.96		S	S	S	S	S	S	S	S	S	S	S	S	
AL2	10.51			S	S	S	S	S	S	S	S	NS	S	S	
AL3	10.27				NS	S	S	S	S	S	S	S	NS	NS	
AL4	10.23					S	S	S	S	S	S	S	NS	S	
AL5	10.08						S	S	S	S	S	S	S	S	
AL6	9.87							NS	S	S	S	S	S	S	
AL7	9.81								S	S	S	S	S	S	
AL8	10.82									S	S	S	S	S	
AL9	10.51										S	NS	S	S	
AL10	10.37											NS	NS	NS	
AL12	10.46												S	NS	
AL13	10.32													NS	
AL14	10.37														
Total															66

S= Significant Comparison
NS=Non Significant Comparison

Energy Absorbed

Means (ak-anova3.sta)
$F(12,143)=192.04$; $p<0.000$

	EA	AL1	AL2	AL3	AL4	AL5	AL6	AL7	AL8	AL9	AL10	AL12	AL13	AL14	
AL1	3.49		S	S	S	S	S	S	S	S	S	S	S	S	
AL2	4.07			S	S	S	S	S	S	S	S	NS	S	S	
AL3	4.35				NS	S	S	S	S	S	NS	S	NS	NS	
AL4	4.40					S	S	S	S	S	S	S	NS	S	
AL5	4.56						S	S	S	S	S	S	S	S	
AL6	4.78							NS	S	S	S	S	S	S	
AL7	4.84								S	S	S	S	S	S	
AL8	3.68									S	S	S	S	S	
AL9	4.07										S	NS	S	S	
AL10	4.24											NS	NS	NS	
AL12	4.13												S	NS	
AL13	4.29													NS	
AL14	4.24														
Total															65

S= Significant Comparison
NS=Non Significant Comparison

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